A TTOP MODEL OF PERMAFROST DISTRIBUTION IN THE BOREAL WETLAND ENVIRONMENT OF WHATÌ, NT, CANADA

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ABSTRACT

Most permafrost models in Canadian boreal forests are low resolution at a regional or continental scale. This study aims to understand the viability of a Temperature at Top of Permafrost (TTOP) model on a local scale in the boreal wetland environment of Whatì, N.T. The model utilizes independent variables of vegetation, topographic positioning index and elevation, with the dependent variable being ground surface temperature collected from 60 Ground Truthing Nodes (GTN). The model predicts that 29 % of the ground is underlain by permafrost by having a mean annual temperature of < 0 °C. Model accuracy is assessed at 62.5 % when compared to ground truthing sites. Most permafrost studies place Whatì in the extensive discontinuous zone estimating that between 50 % - 90 % of the ground is underlain by permafrost. The underestimation and low accuracy show that ground truthing and accuracy assessments in this environment are critical.

PREFACE

Chapter one of this thesis provides a short introduction and the main objectives of the thesis. The literature and background information were reviewed and organized in Chapter two of this thesis. This chapter goes through the permafrost and northern ecosystem temperature modelling to provide context for the remainder of the thesis. This chapter was directed and edited by Philip Bonnaventure, who also assisted with sourcing some of the material.

Chapter two contains a manuscript of the research conducted in the study. The idea for the study was conceived by Philip Bonnaventure, Seamus Daly and me. It was then guided by discussions with my supervisory committee throughout the course of my Master of Science degree. I was the lead on the research and writing of this manuscript. It was then edited by Philip Bonnaventure, Seamus Daly, Madeleine Garibaldi, Will Kochtitzky and me.

Chapter three was organized and written by me with edits and proofreads from Philip Bonnaventure in preparation for this thesis.

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I would like to acknowledge the Tłı̨chǫ Traditional Territory on which this study took place and thank Lisa Nitsiza, the Community Government of Whatì and the generous people of Whatì. I hope this project will benefit the community and those in it for years to come. This project was not possible without a CCPN and NSTP grant, and remote sensing data was provided by Will Kochtitzky.

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LIST OF ABBREVIATIONS

BLR	Bilinear Regression
CAS	Cryotic assessment sites
CB	Coniferous forest burnt
CC	Coniferous forest
DEM	Digital elevation model
EBK	Empirical Bayesian Kriging
EBKRP	Empirical
FDD	Freezing degree days
FDDa	Freezing degree days of the air
FDDg	Freezing degree days of the ground surface
GTN	Ground temperature node
IDW	Inverse distance weighting
LSC	Low-shrub clearing
LSOM	Low-shrub organic matter
MAAT	Mean annual air temperature
MAGT	Mean annual ground temperature
MAGST	Mean annual ground surface temperature
MCS	Microclimate station
MW	Mixed-wooded forest
MWB	Mixed-wooded forest burnt
NN	Natural Neighbour
PF	Permafrost model
n_f	freezing n-factor
n_t	Thawing n-factor
NT	Northwest Territories
PISR	Potential incoming solar radiation
PP	Peat Plateau
PPB	Peat Plateau Burnt
RH	Relative humidity
rk	ratio of thawed to frozen thermal conductivity
RMSE	Root mean Squared error
SF	Seasonal frost model
TDD	Thawing Degree Days
TDDa	Thawing degree days of the air
TDDg	Thawing degree days of the ground surface
TPI	Topographic position index
TTOP	Temperature at top of permafrost
WL	Wetland
WWS	Whatì weather station

Chapter 1: Background

1.1 Introduction

Around 80 % of the world's boreal forests occur in permafrost regions and because of the extreme climate and relatively low precipitation these forests are very responsive to climate change (Helbig et al., 2016; Stuenzi et al., 2021). This is due to a projected increase in insect pest species, quantity and intensity of forest fires and permafrost degradation (Price et al., 2013). Often littered within northern boreal forests are wetland peat-rich environments. These systems are very significant as they act as a carbon sink, containing high amounts (800 Pg) of frozen organic carbon, with the potential to store up to 75 kg C m^{-2}. These soils are subject to decomposition (thermokarst) as permafrost thaws and the climate warms (Apps et al., 1993; Walker et al., 2018). This becomes more concerning with the effects of Arctic amplification – global trends of climate warming are larger and more significant in the Arctic and cold regions than in the rest of the world (Serreze & Barry, 2011). Positive feedback mechanisms, including melting ice and increases in atmospheric water vapour amplifies the greenhouse effect (Winton, 2006; Yoshimori et al., 2014). Surface temperatures in the Arctic have risen on average by 1.36 °C from 1875 - 2008 which is over half a degree higher than the rest of the northern hemisphere (0.79°C) (Bekryaev et al., 2010). It is understood that by 2100 permafrost in the near-surface (permafrost still having a typical active layer relationship where a talik has not yet formed) will be reduced to 15 % of what it was in 1970-1989 (Serreze & Barry, 2011). Taliks are representing areas of unfrozen ground in permafrost regions, they can be above or below 0 °C and their state is determined by their relationship to the permafrost or the reason for the unfrozen area (ACGR, 1988; Van Everdingen, 1998). Permafrost, although vulnerable to thaw as the climate warms, is difficult to quantify in terms of both thermal state and extent without direct in-situ observation (Woo et al., 2008). Unlike other large elements of the cryosphere (e.g. sea ice and glaciers) permafrost extent cannot widely be mapped using optical remote sensing from satellite imagery (Duguay et al., 2005). As a result, determining permafrost attributes and mapping involves extensive fieldwork as well as the use of modelling techniques e.g. (Bonnaventure & Lewkowicz, 2012; Deluigi et al., 2017; Etzelmüller et al., 2006; Farbrot et al., 2007; Garibaldi et al., 2021; Lewkowicz & Ednie, 2004). The current maps and studies used to represent permafrost are created at a regional or national scale (Heginbottom et al., 1995; Obu et al., 2019). This can cause issues when applied on a local scale due to the heterogeneous nature of soil, vegetation, and moisture distribution within boreal forest environments (Jorgenson et al., 2013; Van Cleve et al., 1983). On top of this, variations in soil type, vegetation, microtopography, snow cover and hydrology will also play a role in permafrost distribution in these areas.

Permafrost is the only element of the cryosphere that is inhabited by humans year-round (French & Williams, 2007). The peoples and communities in permafrost regions of northern Canada face considerable uncertainties and challenges associated with permafrost change. Thawing permafrost has been shown to be associated with considerable environmental issues, including the releases of stored carbon (MacDougall et al., 2012), toxins, including mercury (Schuster et al., 2018), ancient viruses and diseases (Legendre et al., 2014), changes in hydrological regimes (Connon et al., 2014) as well as landscape instability and hazards associated with thermokarst (Vincent et al., 2017). Additionally, thaw poses issues for both existing and future infrastructure including buildings, roads and pipelines (Doré et al., 2016). These issues are further exacerbated by natural disturbances common in the boreal forest environment, especially the presence of fire coupled with a general lack of sufficient baseline permafrost distribution information and susceptibility to thaw. As a result, spatial modelling has proven to be the most reliable tool to examine permafrost distribution for scientific and engineering research questions (Etzelmüller et al., 2006).

1.2 Research Objectives

The objectives of this research are to examine the validity of a climatically driven model in a boreal wetland environment, as well as to better understand the heterogeneity of ground temperatures of the discontinuous permafrost zone around Whatì, NT. Given the low relief of the area air temperature should remain relatively constant while the ground temperature will show high variability. By quantifying the surface thermal distribution, we want to understand the role of different environmental variables, which play a role in boreal wetland surface temperature heterogeneity. Using many small sensors known as Ground Temperature Nodes (GTN) a network was deployed to conduct an ecoregional assessment of ground surface temperatures. This study examines the hypothesis that a Temperature at Top of Permafrost (TTOP) approach using a GTN network can determine the spatial distribution of permafrost while providing insight into permafrost thermal state that is equivalent in accuracy to models created using ground truthing techniques (Daly et al., 2022). In addition, we want to assess if creating a viable TTOP model is possible with only one year of data. In order to achieve this goal, mapping and modelling the spatial distribution of ground thermal regimes must be accomplished. This effort uses a combination of an in-situ ground surface temperature network recording field observations to drive a TTOP model in order to compare different modelling approaches (Obu et al., 2019; Smith & Riseborough, 1996, 2002). The final objective is to compare changes in thermal dynamics of disturbed ecosystems vs undisturbed ecosystems. Understanding the thermal dynamics of heterogeneous northern landscapes is imperative to documenting permafrost presence and stability in northern regions.

1.3 Thesis Structure

This master's thesis consists of four chapters. The first chapter will provide an introduction and background on the purpose of the thesis and outline the study's primary objectives. Chapter two will provide a literature review on topics that provide context for this thesis in permafrost environments. These specifically look at topics in environmental controls on permafrost and thermal regimes as well as permafrost mapping and modelling techniques. Chapter three consists of a scientific paper containing the study research and is currently in preparation to submit to the Journal of Permafrost and Periglacial Processes. Chapter four includes the conclusion of the thesis and the potential for future work.

2.1 Introduction

Permafrost is earth materials that remain at or below 0 ˚C for at least two years (ACGR, 1988). The permafrost system and its attributes contribute greatly to the majority of ecosystem processes occurring in boreal wetland environments. Fundamentally, the permafrost system is made up of three major components interacting with one another. These include the permafrost itself, the active layer; the uppermost layer which is subject to annual freeze-thaw and the transient layer, which is an ice-rich zone subject to decadal or century-level freeze-thaw and acts as a buffer between the permafrost and the active layer (Shur et al., 2005).

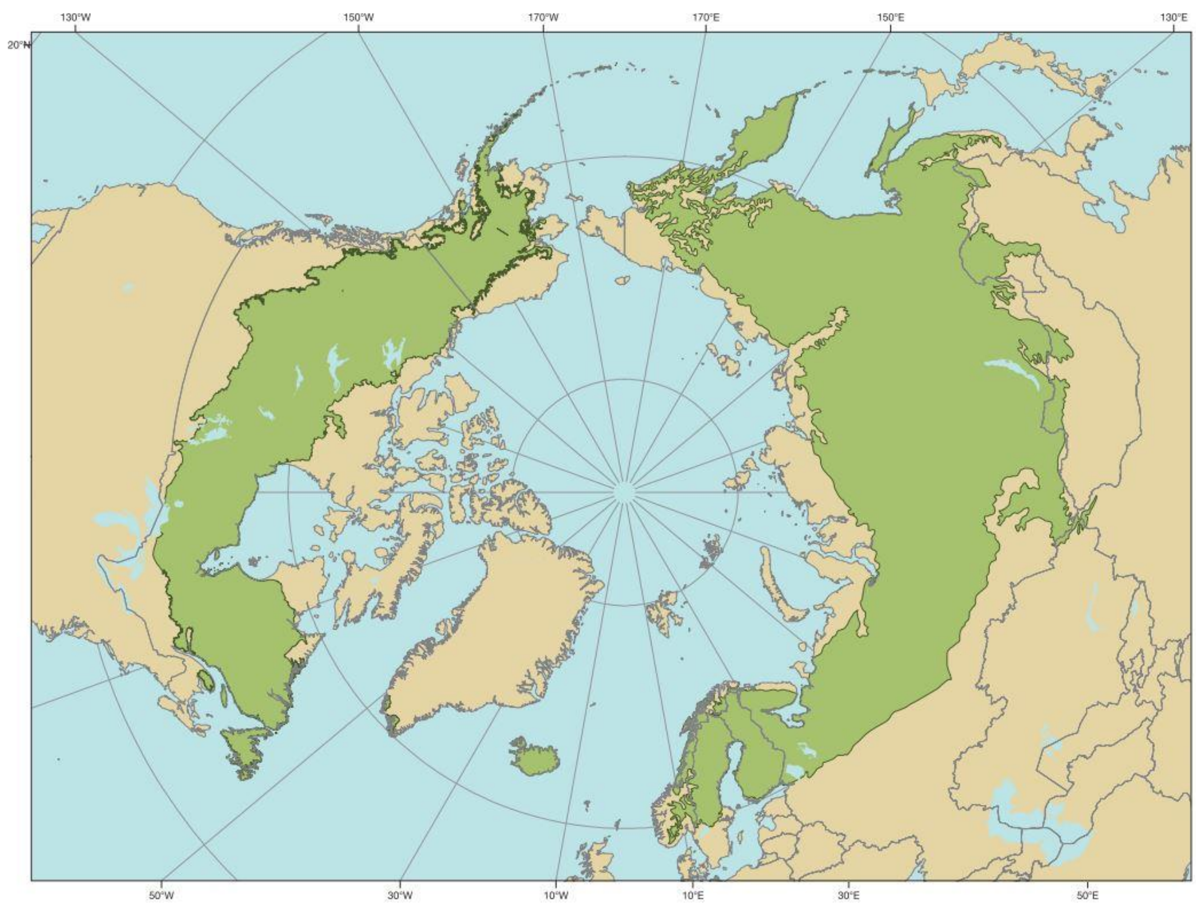

Figure 1. Extent of boreal zones across the globe. Eurasia based on Lavrenko and Sochava (1954), Ahti et al. (1968), Denisov (1970), and (Kurnaev, 1990); North America is that of (Brandt, 2009). (*Permission not Required).*

2.2 Permafrost Types and Classifications

The spatial distribution of permafrost can be classified by the amount of ground that is underlain by it (Obu et al., 2019). It ranges from continuous (>90 %), extensive discontinuous (50 – 90 %), sporadic discontinuous (10 – 50 %) to isolated patches (<10 %) (Heginbottom et al., 1995) (Figure 2). Northern latitudes are more continuous with a deeper, colder permafrost layer, which becomes warmer and thinner in more southern areas. At a regional and continental scale, permafrost is primarily controlled by climate and generally cannot exist where the mean annual air temperature (MAAT) exceeds -2 ˚C. The transition from continuous to discontinuous has been generalized to occur between the -6 ˚C and -8 ˚C MAAT isotherm. At local scales, the important controlling factors of permafrost distribution and ground thermal interactions include snow cover, vegetation, elevation, aspect, topographic positioning index (TPI), thermal conductivity of the soil and soil moisture (Bonnaventure et al., 2017; Bonnaventure & Lewkowicz, 2008; Fisher et al., 2016; Goodrich, 1982; Shur & Jorgenson, 2007; Williams, 1989).

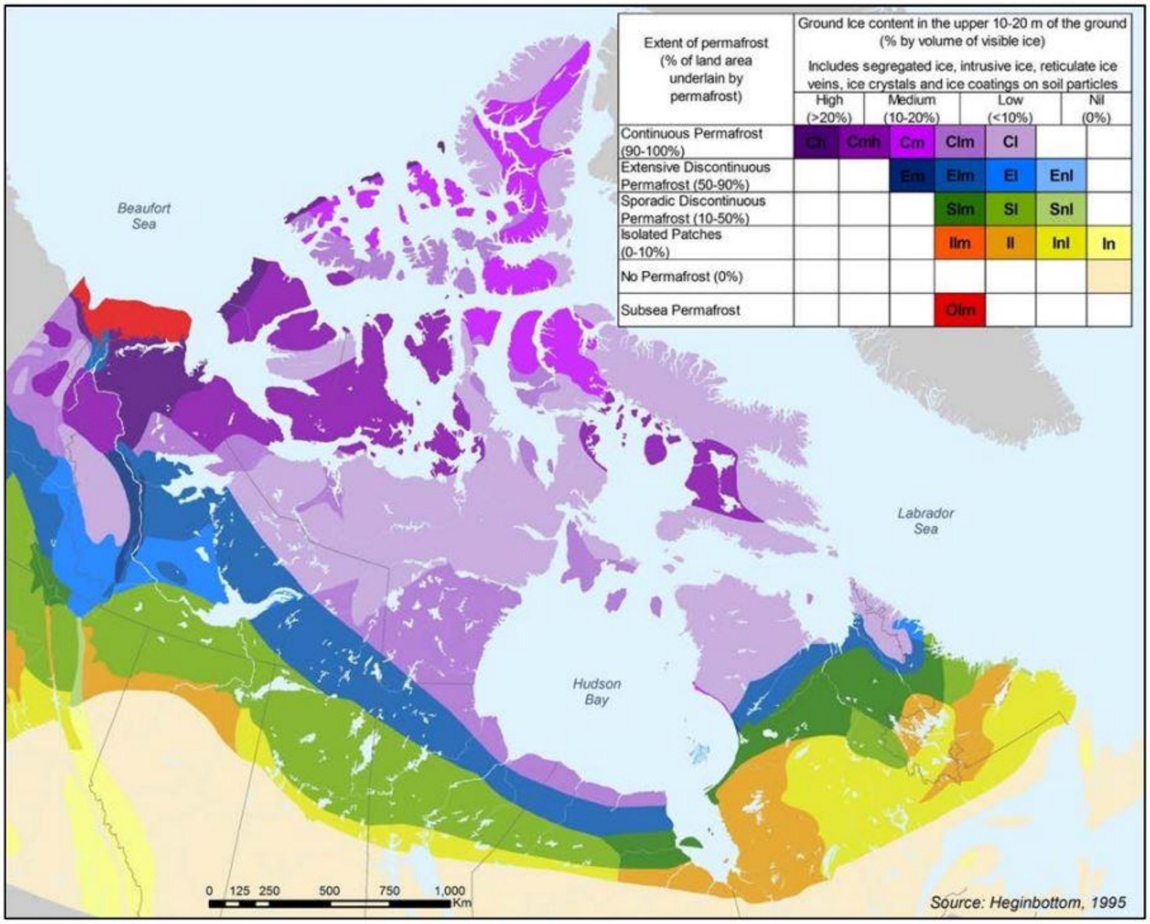

Figure 2. Permafrost map of Canada with zonation and ground ice content produced by Heginbottom et al. (1995). From the National Atlas of Canada, 5th edition, Plate 2.1 (MCR 4177), Generated at scale 1:7,500,00. (*Permission not Required*)

Permafrost stability and the thickness of each of the three components (active layer, transient layer and permafrost) are subject to ecosystem variables on both a macro- and micro-scale (Bonnaventure & Lamoureux, 2013). A large part of permafrost characteristics is determined by the ecosystem it is found in. In boreal forests permafrost is discontinuous and it can exist in areas with an annual MAAT as high as 2 °C and can degrade in areas with MAATs as low as -20°C (French & Williams, 2007). This is due to interactions between topography, soil type, soil moisture, vegetation and snow (French & Williams, 2007). Due to high amounts of organic matter, active layers in boreal forests are generally thin and often do not exceed a depth of 1.5 meters (Bonnaventure & Lamoureux, 2013; Nixon & Taylor, 1998). Mountain permafrost is defined as areas where permafrost is present in areas of high elevation but absent from adjacent lowlands and valleys (Harris & Corte, 1992). Mountain permafrost can be classified as any permafrost continuity classification over short horizontal distances but is generally discontinuous and sporadic due to the influence of topography and the high variability of microclimate it experiences. Mountain permafrost is relatively warm making it vulnerable to climate change (Etzelmüller et al., 2001). The distribution of mountain permafrost will vary with elevation and latitude, as latitude lowers the lower limit of elevation rises (French & Williams, 2007; Harris & Brown, 1981). In mountainous areas of thick bedrock and debris, permafrost will generally have a thick active layer due to low insulative properties. Towards the valley where the soil becomes more developed and there is thicker organic matter, the active layer becomes thinner. Submerged permafrost can occur in ice-rich areas where pooling occurs in the summer as ground ice melts. This pooling can lead to a change in the thermal characteristics of the area as it rises its albedo thus increasing the amount of solar radiation it absorbs (Bonnaventure & Lamoureux, 2013; Woo et al., 2008).

Another widely used classification technique is based on climate, ecosystem and permafrost interactions; (Shur & Jorgenson, 2007) (Figure 3). This includes *Climate-driven* permafrost which occurs in the High Arctic and is driven by cold climates. It forms when unfrozen soil is exposed to the air. This type of permafrost is probably the most vulnerable to a changing climate as it strictly relies on cold temperatures. *Climate-driven ecosystem modified* also occurs in the High Arctic where permafrost forms on a newly exposed surface but then becomes an important part of the developing ecosystem allowing both to grow. *Climate-driven ecosystem protected* is permafrost that forms in cold climate conditions but then a thick layer of mosses or peat develops overtop of it protecting it from warmer conditions and allowing it to be more stable. *Ecosystem-driven* permafrost is probably the most complicated as it is formed through the interaction of biophysical factors that affect soil temperatures across the landscape. These factors will be explained in greater detail in the following sections but are dependent upon the thermal capabilities of snow depth (Zhang et al., 1996), soil thermal regimes (Kukkonen et al., 2020), vegetation shading effects and changes in albedo. *Ecosystem-protected* permafrost occurs in areas where permafrost formed under cold climate conditions but mean annual air temperature (MAAT) has warmed since then and the insulating effects of the ecosystem have allowed the permafrost to persist. This classification technique is useful as it provides background information on permafrost formation and how it currently exists. This is essential for studies and researchers to understand the stability of permafrost in the regions where they are working.

Under these classification standards, permafrost in the boreal forest would be described as extensive discontinuous or sporadic discontinuous with medium to low ice content. According to Shur and Jorgenson (2007), , permafrost in the boreal forest zone can be categorized as climate-driven ecosystem modified (MAAT of -5 °C) in the northern latitudes as temperatures can become cold enough to allow permafrost to aggregate but its presence is dependent on ecosystem types (Daly et al., 2022). In more southern regions of the boreal, permafrost is climate-driven ecosystem protected and ecosystem-driven (MAAT > 0 °C). These types of permafrost generally occur under vegetation with a thick organic layer, If this layer is removed by human clearing or forest fire the permafrost will degrade and could disappear entirely (Bonnaventure & Lamoureux, 2013; Shur & Jorgenson, 2007).

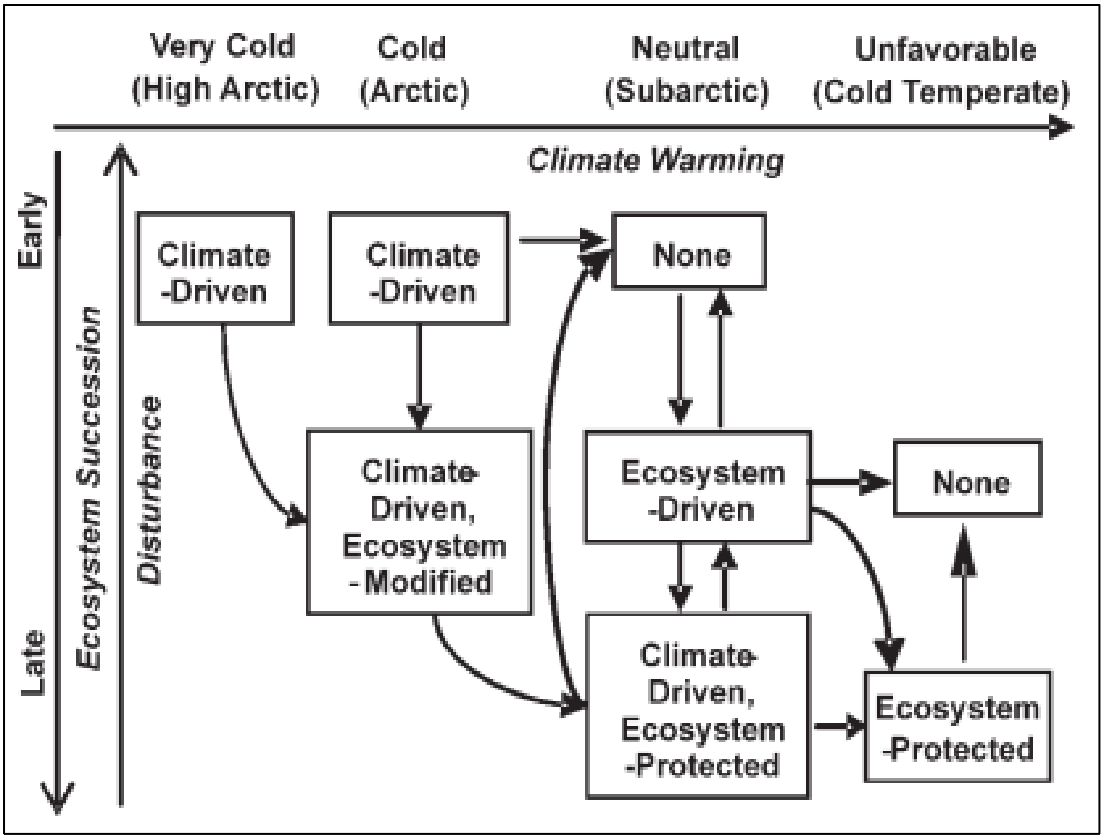

Figure 3. Permafrost classification cycle based on climate-ecosystem interactions (Shur & Jorgenson, 2007). (*Used with Permission*)

2.3 Permafrost and Environmental Features

2.3.1 Topography

In areas of high relief such as the mountainous regions of Alaska or Yukon, topographic related variables play a large role in permafrost presence. These include elevation, slope, aspect, topographic position index (TPI) and potential incoming solar radiation (PISR). All these variables work in combination with one another as elevation, aspect and slope affect PISR and TPI (Bonnaventure & Lewkowicz, 2008). As temperatures generally decrease with elevation permafrost presence can increase at higher elevations (Harris, 1981). However, cold air drainage and pooling can occur, causing temperature inversions and warming air at higher elevations (Burn, 1994; Williams & Burn, 1996). Aspect and slope grade will affect the amount of PISR that an area receives as steep north-facing slopes will receive much less sunlight than south-facing slopes.

Aspect also affects snow deposits as leeward slopes and basins will collect more snow creating more insulation. TPI refers to the elevation and slope of a cell in relation to the cells around it. It plays a large role in snow deposits as snow will be swept from peaks and deposited in depressions providing more insulation for valleys and hollows, leaving peaks and ridges more exposed to the cold air of the winter. TPI will also influence the hydrology of a region if water collects in poorly drained areas potentially either leading to increased vegetation growth which will assist with the insulation of permafrost or it will grow larger causing the development of taliks and thickening of the active layer (Bonnaventure & Lamoureux, 2013; Bonnaventure et al., 2017; Bonnaventure & Lewkowicz, 2008; Bonnaventure & Lewkowicz, 2011; Etzelmüller et al., 2006; Holloway et al., 2020).

2.3.2 Snow

Snow plays a large role in every aspect of northern research. In studying permafrost, the thermal effects of snow on the thermal regime of MAAT and MAGST depend on timing, duration, depth, density and structure (Zhang, 2005). Snowfall over an entire region will dramatically shift a landscape's surface albedo, emissivity, thermal conductivity, and latent heat capabilities. In the boreal forest snow interception plays an important role in permafrost aggradation as snow absence allows cold winter temperatures to lower the MAGST (Figure 4) (Goodrich, 1982; Zhang, 2005). Snow depth works in conjunction with topographic and vegetative variables. The insulation of snow decreases the connectivity between winter MAAT and MAGST, allowing for the ground temperature to remain positive long after the air temperature has gone below 0 ˚C. This allows biological processes to occur into the winter (Bonnaventure et al., 2017; Garibaldi et al., 2021).

2.3.3 Vegetation

Vegetation plays a much more important role in the discontinuous permafrost zone than it does in the continuous zone (Brown, 1973). Vegetation and soil type prove to be one of the largest controlling factors of permafrost presence in areas with little topographic relief (Daly et al., 2022). It plays a role in active layer thickness as poorly drained well-vegetated areas are known to have a thin active layer while coarse-grained well-drained soil will have a thick active layer (Bonnaventure & Lamoureux, 2013; French & Williams, 2007). Important vegetation characteristics that limit the growth of the active layer include leaf area index, moss layer thickness and understory surface moisture (Fisher et al., 2016). Vegetation is known to provide a cooling effect to protect the ground from summer temperatures when the soil is drier (Kukkonen et al., 2020). It also has the reverse effect in the winter when the soil is frozen as it more easily conducts heat from the ground to the atmosphere (Brown, 1973; Luthin & Guymon, 1974). Vegetation also causes a cooling effect through the process of evapotranspiration. This occurs as latent heat is absorbed to evaporate surface water (Yoshikawa et al., 2002). This is especially true in areas with thick organic layers as it has been shown that there is a positive correlation between an increase in organic layer thickness and an increase in permafrost presence (Johnson et al., 2013). Permafrost in the discontinuous region is highly sensitive to organic layer thickness whether that be an increase or a decrease (Johnson et al., 2013; Jorgenson et al., 2001; Luthin & Guymon, 1974; Osterkamp & Romanovsky, 1999; Ou et al., 2016). As vegetation provides thermal insolation to permafrost in boreal forest regions its is understood that ground temperatures will increase as vegetation degrades and this could result in the thickening of the active layer (Chang et al., 2015). Using vegetation and ecosystem types as an indicator in permafrost modelling has been shown to yield higher accuracies of permafrost presence (Daly et al., 2022; Kremer et al., 2011). This coupled with heterogeneity of vegetation in boreal forest landscapes, make high resolution models and maps important for capturing permafrost distribution and ground temperature variations (Daly et al., 2022; Kremer et al., 2011).

2.4 Permafrost Aggradation

All the above variables work in conjunction with one another either generating positive or negative feedback mechanisms that allow for permafrost aggradation, stability, or degradation in the boreal forest.

The formation and aggradation of permafrost in boreal ecosystems can be attributed to the insulating factors of peat and other organic matter. Accumulations of mosses on peatlands lead to highly insulated grounds with low thermal conductivity in the summer. This will then lead to an increase in surface moisture leading to rapid heat loss in the winter/fall. This is especially true if vegetation and tree canopy develops intercepting snow, which will reduce insulation from cold winter temperatures (Zoltai, 1993). This will result in positive feedback mechanisms that will lead to an increase in permafrost aggradation (Vitt et al., 2000; Williams & Burn, 1996).

2.5 Permafrost Degradation

Permafrost degradation can occur in multiple forms, of which many work in combination with one another. The MAGST is regulated by the interactions of surface water, groundwater, soil properties, vegetation, and snow (Jorgenson et al., 2010). Natural disturbance can have detrimental impacts on MAGST and permafrost presence in boreal forests (Shur & Jorgenson, 2007). Natural disturbance can come in the form of climate change, wildfire, hydrology and thermokarsts, while anthropogenic disturbance generally takes place in the form of deforestation or clearing the land for resources or infrastructure. Thermokarst refers to thaw, erosion and subsidence that often occurs at or near the surface in ice-rich permafrost terrain (Jorgenson et al., 2008). Disturbances are important to consider when modelling permafrost as they can assist in explaining different temperature anomalies of similar ecosystems.

To understand future permafrost degradation climate models such as climateNA are used to predict air temperature warming locally (Wang et al., 2016). These models are purely conceptual as MAGST warming on a landscape scale will vary based on all the landscape factors mentioned above. Permafrost in mountain areas can be sensitive to climate change as temperatures at top of permafrost (TTOP) in some areas are around 0 ˚C and therefore very slight changes in temperatures can lead to dramatic changes at the ground surface. Long-term studies have shown that permafrost can remain stable in regions where MAAT and MAGST have risen to positive temperatures when it is protected by a thick organic mat (Nixon & Taylor, 1998; Osterkamp & Romanovsky, 1999). With rising temperatures in northern ecosystems, it is predicted that there will be an increase in drought, heatwaves, and growing season as well as a reduced snowpack, these will lead to an increase in the frequency and duration of wildfires in northern environment (Turetsky et al., 2011; Wang et al., 2015). A forest fire can be linked to permafrost degradation through four main processes. This includes the effects on surface thermal regimes as there is less vegetation to intercept radiation and decrease in albedo, thermokarst development, permafrost recovery and changes to the hydrology and biogeochemistry of the region (Gibson et al., 2018; Holloway et al., 2020). The effects of forest fire on permafrost degradation are determined by burn severity, soil organic layer recovery and post-fire soil moisture dynamics (Yoshikawa et al., 2002). These can be influenced by landscape variables such as soil texture and thermal properties, soil saturation and snow depth. The effects of snow after a fire can be complicated in a forested area as fire will reduce canopy cover allowing for more snow to buildup on the ground creating more insulation and deteriorating permafrost but if the forest is more subject to wind, the snow will be redistributed elsewhere (Holloway et al., 2020; Jafarov et al., 2013). It generally takes the active layer 5 years to restabilize after a fire and can be almost twice as thick after a fire (Gibson et al., 2018; Holloway et al., 2020). Analyzing the effects of fire on permafrost degradation can be very effective and simply done as studies are able to directly compare burnt and unburnt sites. This is also an easy way to assess how rising temperatures affect burnt and unburnt areas differently (Smith et al., 2015).

It is also projected that there could be an increase in precipitation in the form of rain or increase in heavy rain events (Bengtsson et al., 2011). This increase can contribute to the deepening of the active layer by increasing precipitation heat transfer and ground thermal conductivity (Mekonnen et al., 2021). Water and pooling can modify the energy balance of the ground beneath it as it has a very low albedo and a very high heat capacity allowing it to absorb much more radiation than a snowy or vegetated surface (Romanovsky & Osterkamp, 2000). This can lead to a large increase in temperature at the ground surface, increasing thaw. Standing water will also affect the changes in latent heat release and absorption (Riseborough, 1990). Water has the ability to raise the surface air temperature by up to 12°C (French & Williams, 2007). Due to this pooling of surface water acts as a positive feedback mechanism for permafrost degradation (Jorgenson et al., 2010). These can then develop into thermokarst which will eventually form a talik (French & Williams, 2007). Taliks affect water movements and vegetation succession in a region which can change the thermal dynamics of permafrost (Woo et al., 2008).

These mechanisms make modelling permafrost presence and stability a difficult task. They interact with each other at varying levels depending on the ecosystem and landscape of the region. This, combined with the negative feedback of vegetation and organic matter, shows the different biophysical factors that are at play. Factors that cause changes in thermal conductivity, albedo, latent heat and heat capacity all play a different role in ground temperatures and permafrost presence (Jorgenson et al., 2010).

2.6 Climate Change and Ecosystem Disturbance

When modelling climate change and permafrost degradation, increasing air temperatures can be predicted using ClimateNa models RCP 4.5 and RCP 8.5, IPCC as Arctic Climate Impact Assessment (ACIA) models (Bonnaventure & Lewkowicz, 2011; Garibaldi et al., 2021). These models are purely conceptual as MAGST warming on a landscape scale will vary based on all the landscape factors mentioned above. Long-term studies have shown that permafrost can remain stable in regions where MAAT and MAGST have risen to positive temperatures when it is protected by a thick organic mat (Nixon & Taylor, 1998; Osterkamp & Romanovsky, 1999).

With expected warming in northern ecosystems, it is predicted that there will be an increase in drought, heatwaves, and growing season as well as a reduced snowpack and because of this, it is expected that there will be an increase in the frequency and duration of wildfires in northern environments (Turetsky et al., 2011). A forest fire can be linked to permafrost degradation through four main processes, including the effects on surface thermal regimes as there is less vegetation to intercept radiation, a decrease in albedo, thermokarst development, permafrost recovery and changes to the hydrology and biogeochemistry of the region (Holloway et al., 2020). The effects of forest fire on permafrost degradation are determined by burn severity, soil organic layer recovery and post-fire soil moisture dynamics (Yoshikawa et al., 2002). These can be influenced by landscape variables such as soil texture and thermal properties, soil saturation and snow depth. It generally takes the active layer five years to restabilize after a fire and it can be almost twice as thick. Analyzing the effects of fire on permafrost degradation can be very effective and simply done as studies are able to directly compare burnt and unburnt sites of similar ecosystems that can generally be found in close proximity. This is also an easy way to assess how rising temperatures affect burnt and unburnt areas differently (Smith et al., 2015).

2.7 Permafrost Modelling

Modelling in environmental systems attempts to use mathematics, emperical or conceptual solutions to simplify the behaviour of systems. This can involve assumptions about ecosystem processes in order to expand points of data collection across wide areas (Oreskes et al., 1994; Riseborough et al., 2008). Unlike glaciers, vegetation or water features permafrost is in-situ and presence cannot be documented based on observation or satellite imagery. Therefore, accurate modelling of the spatial distribution of permafrost is important. This section goes over some of the more prominent models currently being utilized in permafrost research.

The majority of permafrost models used today are derived from the Heat Flow Theory which calculates the heat capacity of an object based on the amount of thaw at a specific depth and time (Goodrich, 1978). This theory was used to develop models that are primarily utilized outside of permafrost regions where significant freezing and thawing does not occur. To account for this, permafrost models utilize latent heat absorbed and released during the freezing and thawing processes (Riseborough et al., 2008).

2.7.1 Stefan Model

The Stefan Model is common in analyzing active layer depth. The model uses the thermal conductivity of the soil, the index of thawing and freezing expressed and the volumetric latent heat of freezing to determine the depth of thaw over a specific time (Bonnaventure & Lamoureux, 2013; Riseborough et al., 2008). This model is relatively simplistic and therefore requires few, easy-to-obtain parameters including ground thermal conductivity and air temperature (Bonnaventure & Lamoureux, 2013).

In the equation, X is the depth of thaw (m), λ is the thermal conductivity of thawed soils ($W \cdot m^{-1} K^{-1}$), I is the index of freezing or thawing and L is the volumetric latent heat of fusion ($J \cdot m^{-3}$).

Equation 1.

$$X = \sqrt{2\lambda I / L}$$

The Stefan model is most used in wet homogeneous conditions based on the assumption that the temperature of frozen ground is equal to 0 ˚C. This can lead to differences between calculated and measured active layer depths (Bonnaventure & Lamoureux, 2013; Lunardini, 1981; Zhang et al., 2008). Due to this several alterations have been made to the model to allow it to be applicable spatially and temporally.

2.7.2 Kudryavtsev Equation

As the assumptions used in the Stefan equation can lead to errors between calculated and measured thaw depths, the Kudryavstev equation is more accurate in colder regions (Bonnaventure & Lamoureux, 2013; Romanovsky & Osterkamp, 1997). This equation requires significantly more inputs, making it much more complicated. Being one of the most accurate models for calculating active layer depth, the Kudryavstev model requires extensive field variables which can be difficult and expensive to acquire in remote locations (Bonnaventure & Lamoureux, 2013).

Equation 2.

$$X(2\bar{A}C_T + \rho L) = 2\left(A_{gs} - |T_{TOP}|\right)\sqrt{\frac{\lambda_T C_T P}{\pi}}$$

$$+\frac{(2\bar{A}C_T X_{2C} + \rho L X)\rho L\sqrt{\frac{\lambda_T P}{\pi C_T}}}{2\bar{A}C_T X_{2C} + \rho L X + (2\bar{A}C_T X_{2C} + \rho L X)\sqrt{\frac{\lambda_T P}{\pi C_T}}}$$

Where:

Equation 3.

$$\bar{A} = \frac{A_{gs} - T_{TOP}}{\ln\left(\frac{A_{gs} + \frac{\rho L}{2C_T}}{|T_{TOP}| + \frac{\rho L}{2C_T}}\right)}$$

$$X_{2C} = \frac{2\left(A_{gs} - |T_{TOP}|\right)\sqrt{\frac{\lambda_t C_t P}{\pi}}}{2\bar{A}C_T + \rho L}$$

In the equation A_{gs} is the temperature amplitude at the ground surface, C_T is the volumetric heat capacity of the unfrozen ground, L is the volumetric latent heat of water, ρ is soil density, λ is the thermal conductivity of thawed soil and T_{Top} is the temperature at the top of permafrost.

2.7.3 TTOP Modelling

The TTOP model is used to evaluate the connectivity between air temperatures, ground surface temperatures and temperatures at depth to determine ground temperatures and permafrost presence (Figure 4). TTOP is a commonly used model as it simplifies thermal offsets of the air and ground and is important for understanding the interactions between climate and permafrost (Smith & Riseborough, 1996). The current maps and studies that utilize the TTOP model are often created at a regional or national scale and utilize climate indices as a basis for permafrost presence (Figures 5 and 6). These models can often be misleading when applied on a local scale due to the complex role ecosystem structure plays in permafrost distribution, especially as climate changes (Jorgenson et al., 2013; Van Cleve et al., 1983). On top of this, variations in soil type, vegetation, microtopography, snow cover and hydrology also play substantial roles in local-scale permafrost distribution.

Two important variables in the TTOP model are n-factors. These are the ratio of ground surface temperature to air temperature causing surface offsets. They can be split into two different categories: n_t (vegetation offset) which is the difference between summer air and ground surface temperatures due to plant and vegetation cover and n_f (nival offset) which is the difference between winter air and ground surface temperatures due to snow cover effect (Smith & Riseborough, 2002). N-factors are calculated by taking the thawing degree days of the ground and dividing it by the thawing degree days of the air (TDDg) for nt. n_f is calculated the same way but by dividing the freezing degree days of the ground (FDDg) by the freezing degree days of the air (FDDa). (Smith & Riseborough, 1996). FDD and TDD are calculated by taking the absolute summation of daily average temperatures above 0 °C (TDD) and below 0 °C (FDD) for a given time period. N-factors are influenced by the microclimate conditions and latent heat capabilities of the region (Klene et al., 2001). This includes snow, vegetation and soil moisture (Burn, 1998; Karunaratne & Burn, 2003; Klene et al., 2001)

Thermal offset is what controls the formation and stability of permafrost when ground temperatures vary (Osterkamp & Romanovsky, 1999). These offsets can be best represented by differences in mean annual air temperature (MAAT), mean annual ground surface temperature (MAGST), and TTOP (Smith & Riseborough, 2002). Studies that take place on a regional or continental scale will use the TTOP model to understand how MAAT, elevation and precipitation affect permafrost presence (Henry & Smith, 2001; Obu et al., 2019). Studies conducted on a landscape scale attempt to utilize the effects of both macro and micro-scale variables. One issue with this model is that combining it with a long-term warming trend will introduce an error in analytical TTOP modelling as it may take current ground temperatures out of equilibrium with the warming trend observed in the air temperature (Riseborough, 2007).

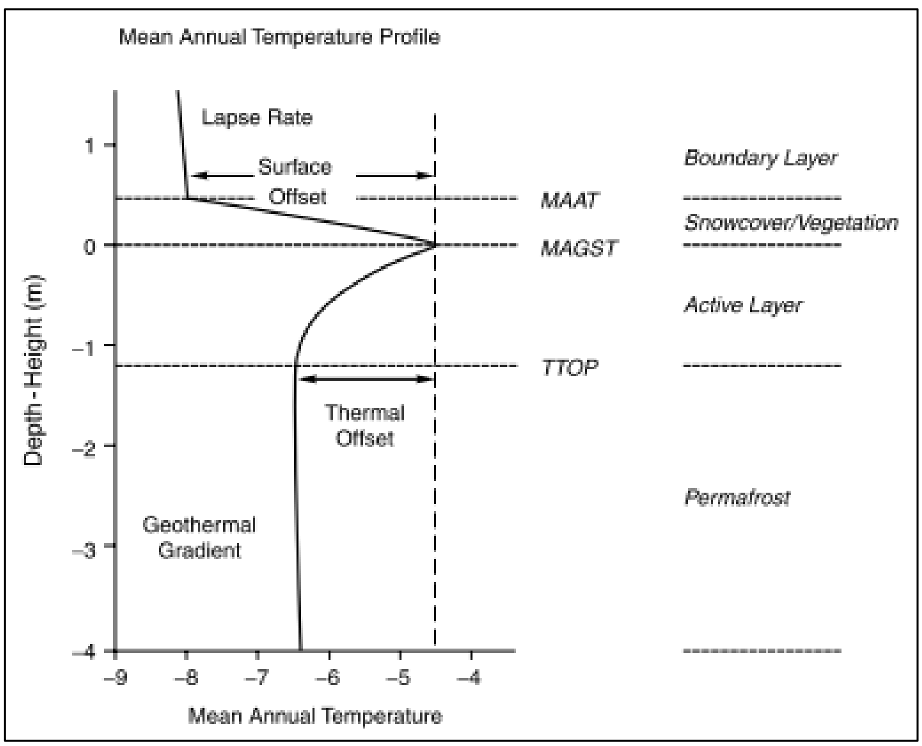

Figure 4. Thermal dynamics used by the TTOP model. This includes the surface offset which is the difference between MAAT and MAGST and the Thermal Offset which is the difference between MAGST and TTOP Smith and Riseborough (2002). (*Used with Permission*)

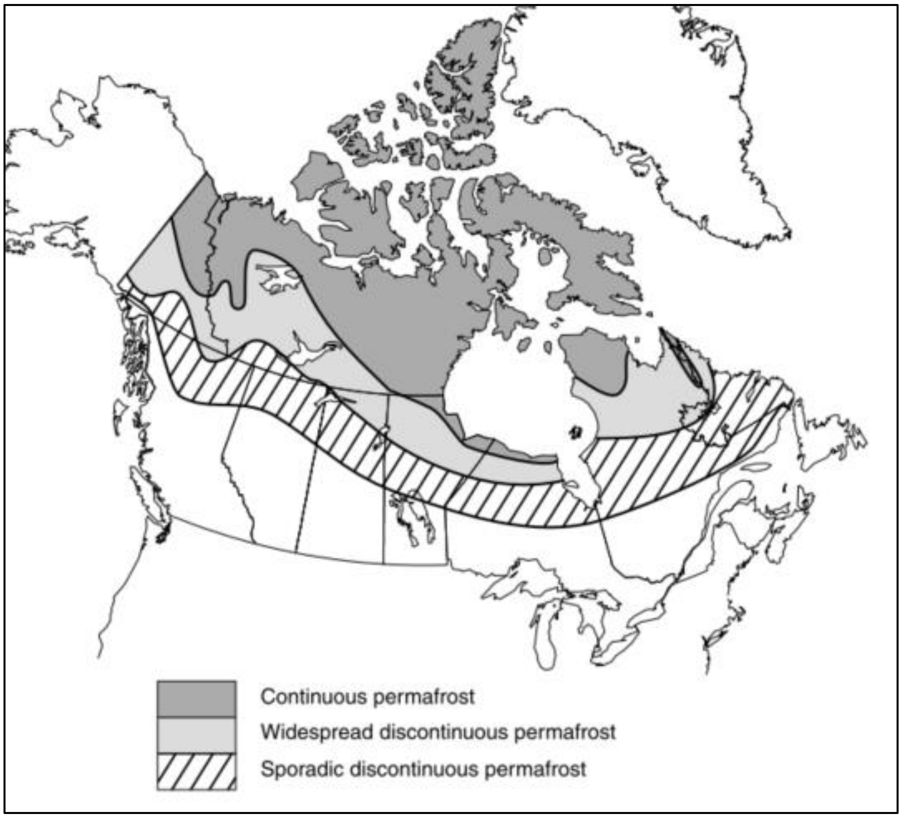

Figure 5. Map of permafrost zones in Canada created using TTOP and climate indices taken from Smith and Riseborough (1996). (*Used with Permission*)

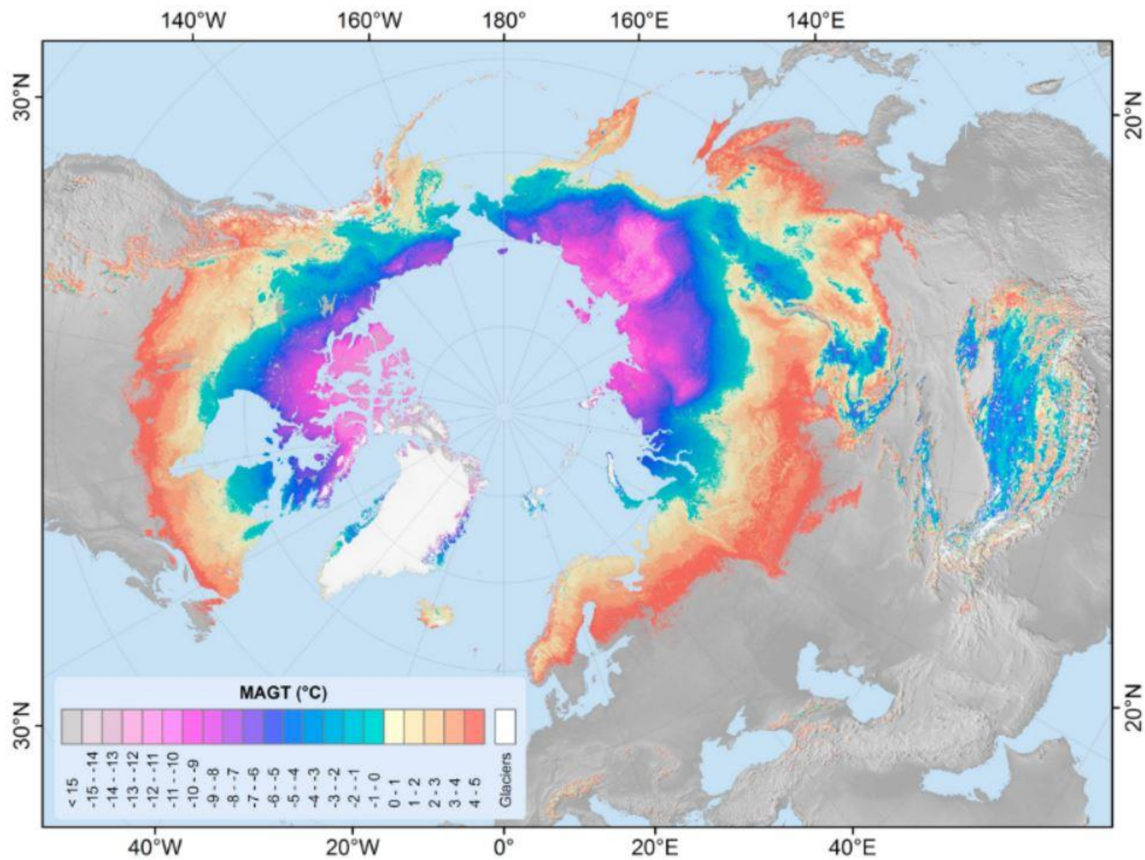

Figure 6. A 1 km^2 Map of global MAGT created using the TTOP model taken from Obu et al. (2019)**.** (*Permission not Required*)

2.7.4 Northern Ecosystem Soil Temperature Model

The Northern Ecosystem Soil Temperature (NEST) model quantifies the effects of climate, vegetation, topographic features and hydrology on energy and moisture transfer between the ground vegetation and atmosphere (Zhang et al., 2003). The model uses heat conduction and energy balance to look at the vertical connectivity of soil vegetation and atmosphere while assuming they are horizontally uniform. By being able to simulate surface energy exchange and the physical processes that effect it (soil heat transfer, snow accumulation and melting, soil thaw and freezing for both permafrost and non-permafrost areas) the model is ideal for accurately calculating transient conditions of a warming climate for long-term modelling (Chen et al., 2003; Zhang et al., 2003). The most significant drawback of this model is that it is computational and parameter heavy making it difficult to collect all the data that are needed for it in remote areas. In areas that show lots of ecosystem heterogeneity inaccuracies can arise based on the input resolution.

2.8 Gaps in Modelling Knowledge

In northern forest fire research, the main gaps in the knowledge are seen regionally (Holloway et al., 2020). The same can be said for permafrost modelling as many studies in North America take place in Alaska and Yukon mountainous regions. There are fewer studies conducted in the Northwest Territories and Nunavut. This has also led to an ecosystem gap as most of the studies conducted in the Yukon and Alaska take place in mountainous terrain,leaving more knowledge gaps in boreal wetland environments. As most of the permafrost modelling in these environments is done on a regional or continental scale, there is more research that needs to be done on the ecosystem mechanisms that contribute to permafrost presence and degradation on a local scale in these areas. Future studies should focus on using a combination of probability models, ground-truthing techniques and accuracy assessments to create the most accurate permafrost presence model. Machine learning models can be useful in evaluating major and minor controlling variables which can vary based on the ecosystem and landscape of the study site (Baral & Haq, 2020; Chasmer et al., 2014; Ou et al., 2016). Knowledge of the region could also greatly benefit from long-term data collection being conducted. As this will improve modelling accuracies.

Chapter 3: Thesis Paper

Modelling Permafrost Distribution using the Temperature at Top of Permafrost Model in the Boreal Forest Environment of Whatì, NT.

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3.1 Abstract

Current permafrost models in Canadian boreal forests are generally low spatial resolution as they cover regional or continental scales. This study aims to understand the viability of creating a temperature at top of permafrost (TTOP) model on a local scale in the boreal wetland environment of Whatì, Northwest Territories from short-term field-collected temperature data. The model utilizes independent variables of vegetation, topographic positioning index and elevation, with the dependent variables being ground surface temperature collected from 60 ground truthing nodes (GTN) and 1.5 m air temperature collected from 10 temperature stations. This study also investigates the relationship vegetation and disturbance have on ground temperature and permafrost distribution. The model predicts that 31 % of the ground is underlain by permafrost, based on a mean annual temperature at TTOP of < 0 °C. This model shows an accuracy of 62.5 % when compared to Cryotic Assessment Sites (CAS). Most inaccuracies came from peat plateaus that had undergone burn in the most recent forest fire in 2014, resulting in out of equilibrium permafrost and climatic conditions. Commonly permafrost mapping places Whatì in the extensive discontinuous zone estimating that between 50 % to 90 % of the ground is underlain by permafrost. The study shows that a climatically driven TTOP model calibrated with CAS can be used to illustrate ground temperature heterogeneity from short-term data in boreal forest wetland environments. However, this approach likely underestimates permafrost extent and is perhaps not the best-suited modelling choice for near-surface permafrost, which is currently out of equilibrium with the current climate.

3.2 Introduction

Around 80 % of the world's boreal forests occur in permafrost regions and because of the extreme climate and relatively low precipitation, these environments are very responsive to climate change (Helbig et al., 2016). Within these northern boreal forests are peat-rich wetland environments. These systems are significant to global climate as they act as a carbon sink, containing high amounts (800 Pg) of frozen organic carbon, with the potential to store up to 75 kg C m^{-2} (Apps et al., 1993). They pose a risk with climate change amplified at high latitudes and the increased susceptibility of the boreal forest due to the extreme climate and low precipitation, these environments will contribute considerably to future carbon emissions through decomposition (thermokarst) as permafrost thaws (Apps et al., 1993; Stuenzi et al., 2021; Walker et al., 2018). Arctic amplification is the phenomenon by which temperature trends and variability are much larger in the Arctic than in the rest of the world (Casagrande et al., 2021; Serreze & Barry, 2011). In addition to carbon release, thawing permafrost poses issues for both the existing environment and infrastructure including buildings, roads and pipelines (Doré et al., 2016). These issues are further exacerbated by natural and anthropogenic disturbances in boreal forest environments, including an increase in forest fires and new infrastructure coupled with a general lack of sufficient baseline permafrost distribution maps or thaw susceptibility. As such, understanding the distribution and vulnerability of permafrost to these changes is critical for planning and hazard assessment in the north today (Etzelmüller et al., 2006).

Permafrost, although vulnerable to thaw, is difficult to quantify in terms of both thermal state and extent without direct in-situ observation (Koven et al., 2013). Unlike other large elements of the cryosphere (e.g. sea ice and glaciers), permafrost extent cannot widely be mapped using optical remote sensing from satellite imagery (Duguay et al., 2005). As a result, determining permafrost attributes and mapping involves fieldwork and modelling (Bonnaventure & Lewkowicz, 2012; Deluigi et al., 2017; Etzelmüller et al., 2006; Farbrot et al., 2007; Garibaldi et al., 2021; Lewkowicz & Ednie, 2004). The current maps and studies used to represent permafrost are often created at a regional or national scale and utilize climate indices as a basis for permafrost presence. (Heginbottom et al., 1995; O'Neill et al., 2019; Obu et al., 2019; Smith & Riseborough, 2002) . These models can often be misleading when applied on a local scale due to the complex role ecosystem structure plays in permafrost distribution, especially as climate changes (Jorgenson et al., 2013; Van Cleve et al., 1983). On top of this, variations in soil type, vegetation, microtopography, snow cover and hydrology also affect local-scale permafrost distribution (Bonnaventure et al., 2017; Fisher et al., 2016; Jorgenson et al., 2001; Karunaratne & Burn, 2003). Permafrost presence and stability in the boreal forest regions is dependent on several variables. These include climatic regions and latitude as well as landscape factors such as snow cover, elevation, vegetation and subsurface conditions including soil type and texture (Smith & Riseborough, 2002).

The objective of this research is to examine the usability of a climatically driven empirical model in a boreal wetland environment. The Temperature at Top of Permafrost (TTOP) has been widely utilized in heterogenous High Arctic environments (Bonnaventure et al., 2017; Garibaldi et al., 2021; Obu et al., 2019). Previous work in Whatì includes a model created by Daly et al. (2022), which determined that ecosystem structure and disturbance history were major influencers in permafrost distribution. This study builds on that work by testing the accuracy of a commonly used TTOP model against their results and identifying regions within the study that present difficulties for the TTOP model. Permafrost in these regions is classified as climate-driven with occurrence associated with low mean annual air temperature (MAAT). Transferring this model to a boreal wetland environment where permafrost can be classified as climate-driven ecosystem-modified, ecosystem-driven or even ecosystem-protected will explore the robustness of short-term climatic inputs to drive permafrost distribution modelling. The terrain surrounding the community of Whatì is a low-relief environment displaying little variability in air temperature while ground temperature varies substantially within the complex ecosystem. Here the TTOP model is created using climatic inputs over a one-year period sourced from a ground temperature node (GTN) and air temperature network (e.g. Garibaldi et al., 2021). The aim of this study is to examine if this model is suitable to determine the spatial distribution of permafrost while providing insight into permafrost thermal state that is equivalent in accuracy to a model created using ground truthing techniques paired with environment-specific variables (Daly et al., 2022). As permafrost distribution in this environment is highly subject to ecological structure, hydrology, and disturbance we test the hypothesis that a climatically driven model like TTOP is likely to underpredict permafrost distribution in this rapidly changing climate and is thus not the best modelling choice given short-term datasets during a period of changing climate.

3.3 Study Area

The study area is delineated by the municipal boundary of the community of Whatì NT, an area roughly 60 km² approximately 165 km northwest of Yellowknife, NT (Government of Northwest Territories, 2022). The community has until recently only been accessible by aircraft or winter roads but was connected to the all-season road network in November 2021.

Whatì is located on the south-eastern shore of the third largest lake in the Northwest Territories, Lac La Martre. Whatì is in a subarctic climate with cool summers and year-round precipitation according to the Köppen-Geiger climate index (Peel et al., 2007). This climate is primarily a factor of its high latitude, continental location, and proximity to water bodies.

According to Environment and Climate Change Canada average air temperature from 2019-2021 in Whatì was -5.9 ˚C (ClimateData.ca). The elevation of the study area ranges from 238 m asl to 282 m asl. Whatì is classified to occur within the extensive discontinuous permafrost zone meaning that 50 – 90 % of the ground is underlain by permafrost (Heginbottom et al., 1995). A recent assessment of permafrost distribution in Whatì by Daly et al. (2022) predicted that the area had 50.0 % permafrost coverage that was highly controlled by ecosystem type. They found that ecosystem classes with the highest probabilities of permafrost (100 %, 99.9 %, 99.0 % and 71 %) included coniferous forest, peat plateau burnt, peat plateau and low-shrub organic matter while mixed-wooded forest burnt, low-shrub clearing, and wetlands generally contained the lowest probabilities (26.1 %, 30.9 % and 32.9 %). Permafrost in Whatì is considered "warm", having a temperature between (0 °C to -2 °C) and is classified as climate-driven, ecosystem-modified (Heginbottom et al., 1995; Henry & Smith, 2001; Shur & Jorgenson, 2007).

The primary species of vegetation found throughout the study area are spruce trees (*Picea*), deciduous trees such as aspen (*Populus*) and willow (*Salix*), Labrador tea (*Rhododendron*), buffaloberry (*Shepherdia*), fireweed (*Epilobium*), bearberry (*Arctostaphylos*) and mosses and lichens including peat moss (*Sphagnum*), reindeer lichen (*Cladonia*) and feathermoss (*Ptilium*). Ecosystem types in this region can be divided into nine sections; coniferous forest, coniferous burnt, mixed-wooded forest, mixed-wooded forest burnt, peat plateau, peat plateau burnt, wetland, low-shrub organic matter, and low-shrub clearing (Daly et al., 2022). A main characteristic of boreal wetland environments is the frequent occurrence of forest fires. These fires assist with a number of ecosystem processes including tree recruitment, vegetation recovery and changes in soil temperature and moisture (Holloway et al., 2020; Kasischke & Turetsky, 2006; Van Cleve et al., 1983). Whatì went through a record forest fire season in 2014. The fire stopped short of the built community due to anthropogenic and natural firebreaks (Daly et al., 2022). These burns play a large role in boreal forest permafrost thaw as they remove trees that intercept snow, creating more insulation from winter temperatures, and can remove the organic layer above the permafrost that insulates it from warm summer temperatures (Yoshikawa 2002).

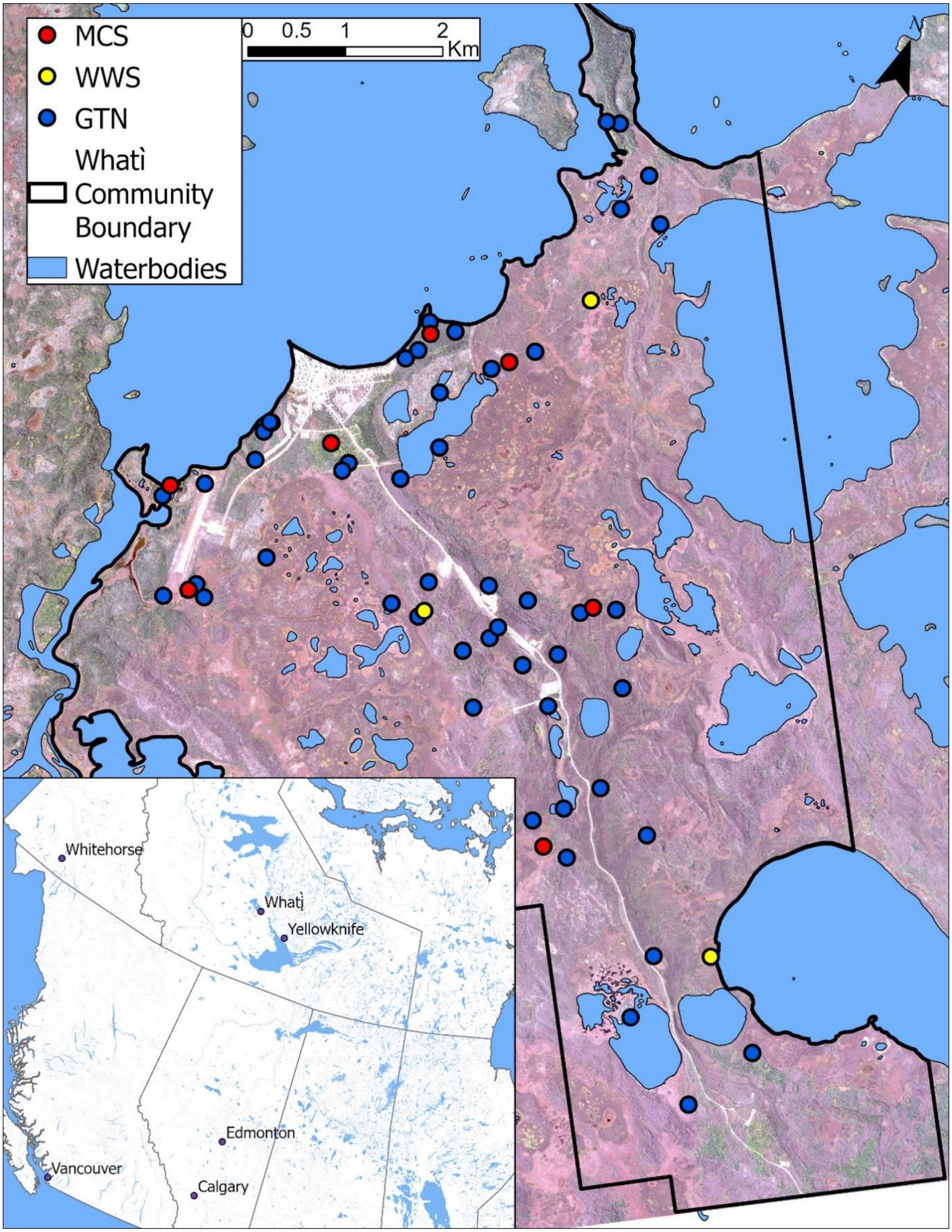

Figure 7. Study area extent in and around the community of Whatì as well as the location of ground temperature nodes (GTN), microclimate stations (MCS) and Whatì weather stations (WWS). Imagery © [2017] DigitalGlobe, Inc.).

3.4 Methods

3.4.1 Data Collection and Pre-setup

A network of air and ground temperature loggers were installed in and around Whatì between 2019-21. These stations were deployed to maximize the spatial coverage and heterogeneity in this environment, specifically focusing on maximizing the sampled variability of factors influencing permafrost distribution.

Locations for all sensor types were predetermined using stratified random proportional sampling based on the amount of landcover of each vegetation type, elevation, and TPI. In some instances, this was modified in the field due to the accessibility and accuracy of vegetation classification. The network of air sensors was installed in 2019 and consisted of seven microclimate stations (MCS) equipped with Hobo (Onset, USA) MX2301A and MX2303 loggers to collect hourly relative humidity (RH), air and ground surface temperatures along with temperature at a ground depth (1.5 m below the surface). These loggers have an accuracy of +/- 0.2 °C and +/-2.5 % RH. Along with these, 3 weather stations (WWS) equipped with HOBO RX3000 measure temperature (accuracy: +/- 0.2 °C), RH (+/-2.5 % RH), windspeed (+/-1.1 m/s), wind direction (+/-5 °), gust speed (+/-1.1 m/s), rain (+/- 1 %), solar radiation (+/- 10 W/m^2), and dew point (+/- 0.25 °C) were set up in 2019 in burnt and unburnt mixed-wooded forests, burnt and unburnt coniferous forest, and burnt and unburnt peat plateaus (Table 1).

Due to the variability of permafrost distribution outlined in Daly et. al (2022), an additional fifty ground temperature nodes (GTN) (Hobo MX2201) were deployed in September 2020 to measure the ground temperature every hour. These have an accuracy of +/- 0.5 °C and were placed 1 – 5 cm below the ground surface. These sites were selected using stratified random proportional sampling based on the amount of landcover of each vegetation type, elevation, and TPI (Table 1). Some compromises had to be made as some sites in the study area could not be accessed.

DEM derived variables that are primarily used in permafrost studies are aspect, elevation, potential incoming solar radiation (PISR) and topographic position index (TPI; (v. 1.3a, Jenness Enterprises, 2006) (Etzelmüller et al., 2006; Riseborough et al., 2008). According to Daly et. al., (2022) the low relief of the area made PISR and aspect irrelevant variables to the model, so they were not considered in ground temperature site selection. TPI refers to the elevation and slope of a cell in relation to the cells around it. TPI influences site hydrology, snow accumulation and redistribution as hollows favor the collection of snow. The calculation for TPI was taken from Daly et al. (2022) and is shown in Equation 4 (Weiss, 2001). Where scalefactor is the outer radius in map units, lrad is inner radius of annulus cells and orad is the uter radius of annulus cells. Elevation and TPI were derived from a 2 m DEM provided by GeoEye optical imagery taken on 17 September 2017 (Imagery © [2017] DigitalGlobe, Inc.). The elevation model was produced by the Polar Geospatial Center at the University of Minnesota using the surface extraction with TIN-based search and space minimization algorithm (Noh & Howat, 2017). Due to the low topographic relief of the area, elevation effects permafrost indirectly as higher elevations in the study area are associated with more gravelly soils and larger rocks not conducive to the presence of permafrost while lower elevations were observed to have more silty and loamy soils (Daly et al, 2022). Elevation is important as it is utilized as a proxy for soil types and texture.

Equation 4.

$$tpi < scalefactor > = int((dem - focalmean(dem, annulus, irad, orad)) + 0.5)$$

As vegetation type is highly heterogeneous, previous studies exposed it as a controlling factor in permafrost distribution (Daly et al., 2022). As such, this was a primary variable for selecting sites especially ground logger locations (Yoshikawa et al., 2002). The Whatì boundary was split up into nine vegetation types, this includes coniferous and mixed-wooded forest burnt and unburnt forests, burnt and unburnt peat plateaus, wetlands, low-shrub organic matter and low-shrub clearings (Daly et. al., 2022).

Table 1. Model input variables for ground sensors including vegetation class, description (Daly et al., 2022), number of sensors (n), number of sensors with a full year of data from October 1, 2020, to September 30, 2021 (n(365)), and landcover percentage of the study area.

Variable	Class	Description	n	n(365)	Coverage (%)
Vegetation Classification	Coniferous Forest (CC)	Black spruce and tamarack tree stands w/, organic mat. layer including moss, lichen, Labrador tea, cinquefoil.	9	7	8.3
	Coniferous Forest Burnt (CB)	Same as Coniferous Forest with grass of Parnassus, sedges, and horsetails. Visible evidence of recent burn (2014).	7	7	9.2
	Mixed-Wooded Forest (MW)	Aspen, birch, willow, spruce, alder w/ thin organic mat. layer. Rose, buffalo berry, bear berry, occasional thin layer of moss and lichen.	5	4	2.9
	Mixed-Wooded Burnt (MWB)	Same as Mixed-Wood Forest w/ fireweed. Visible evidence of recent burn (2014).	10	10	18
	Peat Plateau (PP)	Visible plateau or hummocky terrain. Cloudberry, bog rosemary, white lichen, moss, Labrador tea, spruce tree stands.	5	4	3.2
	Peat Plateau Burnt (PPB)	Same as Peat Plateau with visible evidence of burn (2014).	7	6	8.7
	Wetland (WL)	Wet moss layer, grass, bog birch, fireweed, sundew, wax mertle, willow, cinquefoil, bog rosemary. High water table. Minimal resistance to soil probe.	6	5	36.6
	Low-Shrub Organic Matter (LSOM)	Coniferous Forest adjacent, similar organic mat., low-density to no tree cover. Juniper, willow, spruce, Labrador tea, moss, lichen, cinquefoil.	8	7	12.7
	Low-Shrub Clearing (LSC)	Low-density paper birch, willow. Rose, horsetail, fireweed, and grass	3	3	0.5
Elevation	1	<246 m asl.	12	11	23.3
	2	246 - 250 m asl.	14	12	37.8
	3	250 - 255 m asl.	20	17	24.4
	4	255 - 261 m asl.	6	5	9.8
	5	261 - 282 m asl.	8	8	4.6
Topographic Positioning Index (TPI)	1	<-0.8	6	4	14.2
	2	-0.8 - 0.0	24	22	33.9
	3	0.0 - 1.1	21	18	44.2
	4	1.1 - 8.9	9	9	7.7

Site observations at each of the GTNs included major vegetation types, considering ground cover, the presence of organic mat including moss and lichen, and general substrate type. The geographic position was recorded using a handheld GPS (Garmin GPSMAP 64x Series) using waypoint averaging (accuracy of 1-4 m).

Data from the GTN and MCSs were collected in October 2021 to ensure a full year of temperature data had been measured. During data collection, site observations were made for a second time to note any changes in sites from the previous year. WWS data was received bi-weekly via telemetry from HOBOlink.com. Air temperature data were also collected from Whatì station 1674 from the Canadian Center for Climate Services (CCCS; climatedata.ca)

3.4.2 Temperature Typicality

To ensure that the data were collected in a typical year, temperature typicality needs to be established for air temperature during the time data collection occurred (Garibaldi et. al, 2021). This ensures that the weather in 2020 and 2021 was not an anomaly and the findings can be compared to other studies that occurred at different times. To do this, daily average air temperature data from 1970 to 2021 was taken from the CCCS. As Whatì station 1674 was only established in 1997, data from Yellowknife station A were used. This station is located approximately 150 km SE of Whatì. The daily average temperature data was converted to an annual average, a 10-year average (2011 – 2021) and a 50-year average (1970 – 2021). From there the standard deviation was calculated and these results were compared to the 2020 and 2021 annual average temperatures.

3.4.3 Modeled Surfaces

3.4.3.1 Air Temperature Model

Due to the low relief of the area, elevation was not considered when generating air temperature surfaces (Daly et al., 2022). To generate a mean annual air temperature surface (MAAT) hourly data from October 2020 to September 2021 was converted to an annual average and ran through an inverse distance weighting interpolation technique in ArcGIS Pro 2.9 (ESRI, USA).

3.4.3.2 Ground Surface Temperature Model

To create ground surface temperature surfaces a multivariable linear regression model was first used to determine the significance between mean annual ground surface temperature (MAGST) and different topographic variables. These variables include vegetation, TPI, elevation and soil moisture. Soil moisture was generated by creating a topographic wetness index in ArcGIS. This was done by deriving slope, flow direction and flow accumulation using the DEM. Elevation was used as most topographic features were associated with sandier gravely soils while lower elevations became siltier (Daly et., al, 2022). The TPI and Elevation surfaces were reclassified using natural breaks (Jenk's methos). This is a data clustering method that is designed to reduce variance within classes and maximize the variance between classes (Jenks, 1967) to identify the presence of topographic features. The vegetation surface was taken from Daly et., al, 2022. This surface used vegetation field observations to inform a supervised classification on satellite imagery to derive a spatially complete vegetation map in ENVI (ENVI. Version 5.5, L3 Harris Geospatial Solutions; 2008). Vegetation, TPI, and elevation had significant p values greater than 0.05 and therefore where the three independent variables used in the model creation and where the same variables used in Daly et al., 2022. Soil moisture was the only variable that produced an insignificant P-value and was therefore removed. To generate a MAGST for the entire study area hourly data from October 2020 to September 2021 was converted to an annual average and ran through an EBK regression prediction in ArcGIS Pro with the three identified independent variables.

3.4.3.3 TTOP Variables

Hourly air and ground surface temperature data was collected from each of the sites in October of 2021. Data was converted from hourly measurements to daily averages. Using daily averages freezing and thawing degree-days were calculated at each site for the ground surface

(FDDg and TDDg) and air (FDDa and TDDa). These were calculated by taking the absolute summation of daily average temperatures above 0 °C for TDD and below 0 °C for FDD for October 2020 to September 2021 (Garibaldi et al., 2021). At MCS and WWS sites n-factors were calculated directly. At GTN sites n-factor (Equation 1) calculations used the FDDa and TDDa values from the nearest air temperature stations (e.g. Bonnaventure et al., 2017, Garibaldi et., al, 2021). rk values represent the ratio of thermal conductivity between thawed and frozen ground (Bonnaventure et al., 2017; Way & Lewkowicz, 2018). rk values for each of the sites were determined using vegetation type and known, previously used rk values (Obu et al., 2019; Romanovsky & Osterkamp, 1995; Smith & Riseborough, 2002; Way & Lewkowicz, 2016). These values were 0.2 for peat plateaus, 0.6 for burnt peat and wetlands, 0.3 for coniferous forests, 0.5 for burnt coniferous forests, 0.4 for low-shrub organic mat and 0.8 for deciduous forests, burnt deciduous forest and low-shrub clearings.

3.4.3.4 TTOP Model

The TTOP surface was created using the surfaces generated for each variable required as an input (Equation 6). The n_f surfaces were generated by taking the FDDg surface and dividing it by the IDW derived FDDa surface (Equation 5). The same was done to generate n_t using TDDa and TDDg (Equation 5). The rk surface was generated by assigning each vegetation class its own rk value based on field measurements and past literature (Obu et al., 2019; Romanovsky & Osterkamp, 1995; Smith & Riseborough, 2002; Way & Lewkowicz, 2018). P is the period of time in days and for this study represents 365. These surfaces were then combined with the FDDa and TDDa surfaces using the TTOP model to generate a TTOP surface.

Equation 5.

$$n_f = \frac{FDD_g}{FDD_a} \; and \; n_t = \frac{TDD_g}{TDD_a}$$

Equation 6.

$$\text{TTOP} = \frac{(nt * TDDa * rk) - (nf * FDDa)}{P}$$

3.4.4 Accuracy Assessment

To assess the accuracy of the TTOP model on permafrost distribution the generated TTOP surface was compared to 137 out of 139 binary (permafrost present or absent) cryotic assessment sites (CAS) produced by Daly et. al, (2022). CASs determined the presence or absence of near-surface permafrost using a thermal probe equipped with four thermistor cables (E348-TMC6-HD, accuracy: < ±0.2 °C, resolution: < ±0.03 °C). Thermistor sensors were spaced at 0, 25, and 50 cm from the maximum depth (bottom of probe) with one additional thermistor used to measure the ground surface temperature. If the generated TTOP surface had a temperature of less than 0 °C at a CAS where permafrost was determined to be present, the site was assessed to be correct. A site was also deemed to be correct if the generated TTOP surface had a temperature greater than 0 °C with no permafrost present at the CAS. False positives occurred where the TTOP temperature was less than 0 °C at a CAS where no permafrost was present and false negatives occurred at sites where the TTOP temperature was greater than 0 °C and permafrost was present at the CAS.

3.4.5 Permafrost and Seasonal Frost Model

The seasonal frost model was initially introduced by Smith and Riseborough (1998). To be used in conjunction with the TTOP model for areas that exhibit seasonal frost and don’t have permafrost. Majority of studies utilizing the permafrost model overlook this and strictly use the TTOP model. As the TTOP model is meant for areas where permafrost occurs as it can lead to the underestimation of MAGT in areas where frost is only seasonal, or no frost is present. In these instances, a seasonal frost model should be used. Permafrost in this region is considered warm having a temperature of 0 °C to -2 °C (Daly et al., 2022; Heginbottom et al., 1995; Henry & Smith, 2001). Because of this, the same variables were run through an adapted seasonal frost model and permafrost model (Equation 7). The TTOP surface was then divided into areas greater than 0 °C and areas below 0 °C and both models were run on each of those. To assess the sensitivity of the TTOP model cells with a value between -0.5 °C and 0.5 °C were extracted from the TTOP surface and again both models were run on those cells. The same was then done for cell values between -1 °C and 1 °C.

Equation 7.

$$\mathrm{SF} = \frac{TDDg - (\frac{1}{rk} * FDDg)}{P}$$

3.5 Results

3.5.1 Temperature Typicality

To determine if this limited-term study was conducted over a typical climatic year typicality was examined. The mean annual air temperature in Yellowknife from 1970 to 2019 was -4.2 °C with a standard deviation of 1.3 °C. The temperature range for the 50-years was -7.1 °C (1982) to -1.1°C (1998). During the ten-year period (2011-2021), it was warmer with an average of -3.9 °C and a standard deviation of 0.9 °C. Average temperatures for 2020 and 2021 were -4.9 °C and -4.5 °C. This falls within the 50-year standard deviation of 1.3 °C. For the 10-year average 2020 was within the standard deviation but 2021 was outside by 0.1 °C. Mean annual precipitation for the 10-year period (2011 – 2021) was an average of 258.6 mm with 126.1 mm of snow and 170.8 mm of rain, with a standard deviation of 48.7 mm. The study period of October 1, 2020 – October 1, 2021, was drier than the 10-year average, having a total precipitation of 202 mm with 92.3 mm of snow and 151.9 mm of rain.

3.5.2 Field results

Out of the 10 air temperature sensors, 6 recorded a full year of data from October 1st, 2020, to September 31st, 2021, with a MAAT of -5.3 °C and a range of -5 °C to -5.4 °C. This is 0.7 °C warmer than the Whatì Environment and Climate Change station MAAT of -6.0 °C. This places Whatì within the widespread discontinuous permafrost zone (Heginbottom et al., 1995; Smith & Riseborough, 2002). Out of the 60 total ground surface temperature sensors, 53 recorded a full year of data. This included 48 GTNs, three weather stations, and two microclimate stations. The MAGST of these 53 sensors was 1.5 °C, with a range of -2.2 °C to 4.1 °C.

3.5.2.1 Ground Surface Temperature

The average of MAGST for all sensors was 1.5 °C ranging from -2.23 °C to 4.1 °C. Vegetation was broken up into nine classes. The classes with the lowest MAGST were mix-wooded forest (0.2 °C), coniferous forest (0.4 °C) and peat plateau (0.5 °C). The highest temperatures were seen in the wetland (2.8 °C), low-shrub organic matter (2.1 °C), peat plateaus burnt (1.9 °C) and low-shrub clearing (1.9 °C). In the middle is coniferous forest burnt (1.7 °C) and mix-wooded forest burnt (1.8 °C). For daily average ground surface temperature mixed-wooded forest burnt had the largest range of values with a maximum of 17 °C and a minimum of -8 °C. Ecosystems with low organic matter such as mixed-wooded forest burnt, low-shrub clearing and wetlands had the largest annual range of daily average ground temperatures (25.2 °C, 23.6 °C and 22.9 °C). While ecosystems with high organic matter content such as coniferous forest burnt, coniferous forest, peat plateau and peat plateau burnt had the lowest annual range of temperatures (19.6 °C, 19.9 °C, 20.4 °C, 20.4 °C; Figure 8.).

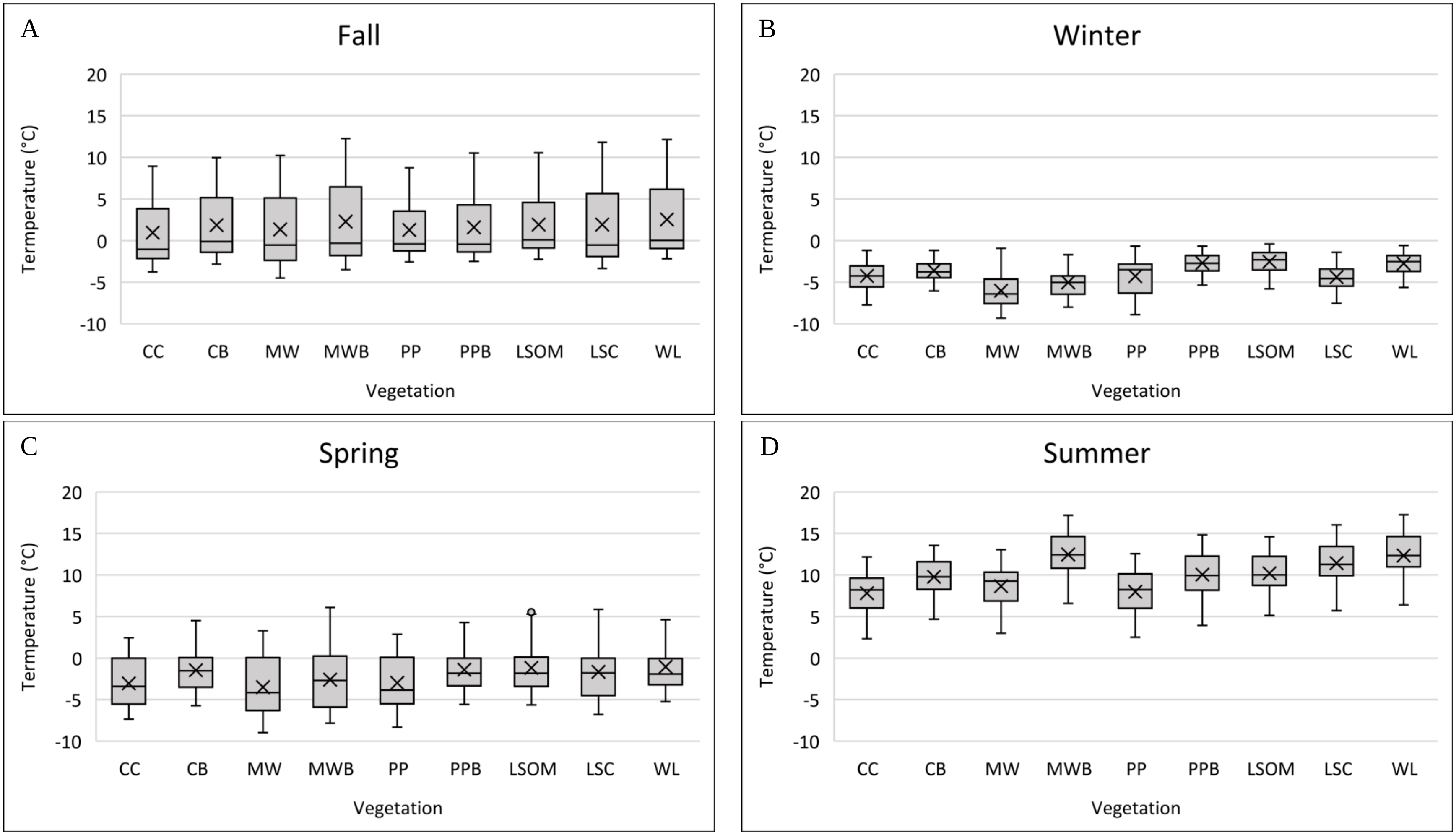

Figure 8. Box and whisker plots showing MAGST temperature ranges of all surface sensors, mean (x), median (-) and outliers for each vegetation and meteorological seasons. (A) Fall from October 1 to November 30, 2020, and September 1 to 30, 2021. (B) Winter from December 1, 2020, to February 28, 2021. (C) Spring from March 1 to May 31, 2021. (D) Summer from June 1, to August 31, 2021.

Calculating cumulative FDD shows the lag in cooling between the air and ground surface temperatures (Figure 9). Cumulative FDDg ranged from a low of 176.3 degree-days at GTN 02 in the Wetland, to a maximum of 1957.1 degree-days at GTN 13 in the mixed wooded forest ecoregion. On average lowest FDD values occurred in low shrub organic matter (441.4) and the highest occurred in mixed-wooded forests (1001.6). Lower FDDg values can be associated with greater amounts of snow and organic values whereas higher FDD is associated with lower snow and less organic matter (Goodrich, 1982; Jorgenson & Osterkamp, 2005). Cumulative thawing degree days shows the differences in ground and air temperatures. Cumulative TDDg ranged from a low of 449.1 degree-days at GTN 19 in the coniferous forest burnt, to a maximum of 1795.4 degree-days at GTN 34 in the mixed-wooded forest burnt. On average lowest TDD values occurred in coniferous forest (919.7) and the highest occurred in mixed-wooded forests burnt (1501.8)(Figure 10). Higher TDD values indicate less amounts of organic matter and vegetation cover.

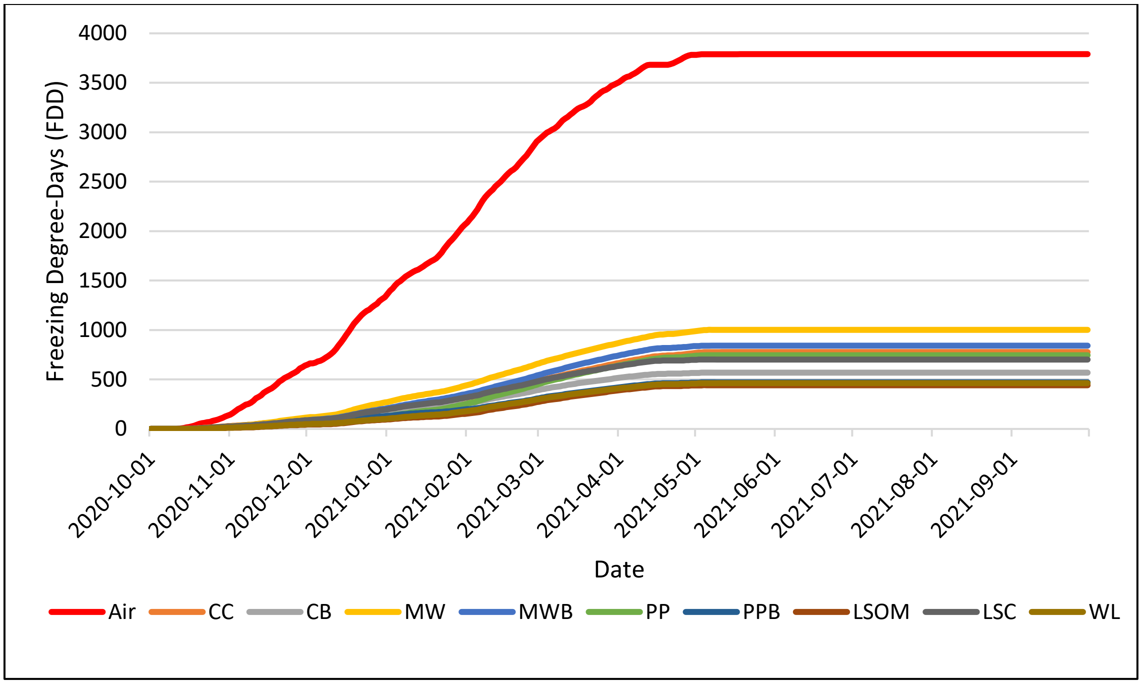

Figure 9. Measured cumulative freezing degree-days (FDD) for all vegetation classes and one air temperature station WWS3 (red). Higher FDD values indicate less organic matter and lower snow cover. Where CC = Coniferous Forest, CB = Coniferous Forest Burnt, MW = Mixed-wooded Forest, MWB = Mixed-wooded Forest Burnt, PP = Peat Plateau, PPB = Peat Plateau Burnt, LSOM = Low-shrub Organic Mat., LSC = Low-shrub Clearing and WL = Wetland.

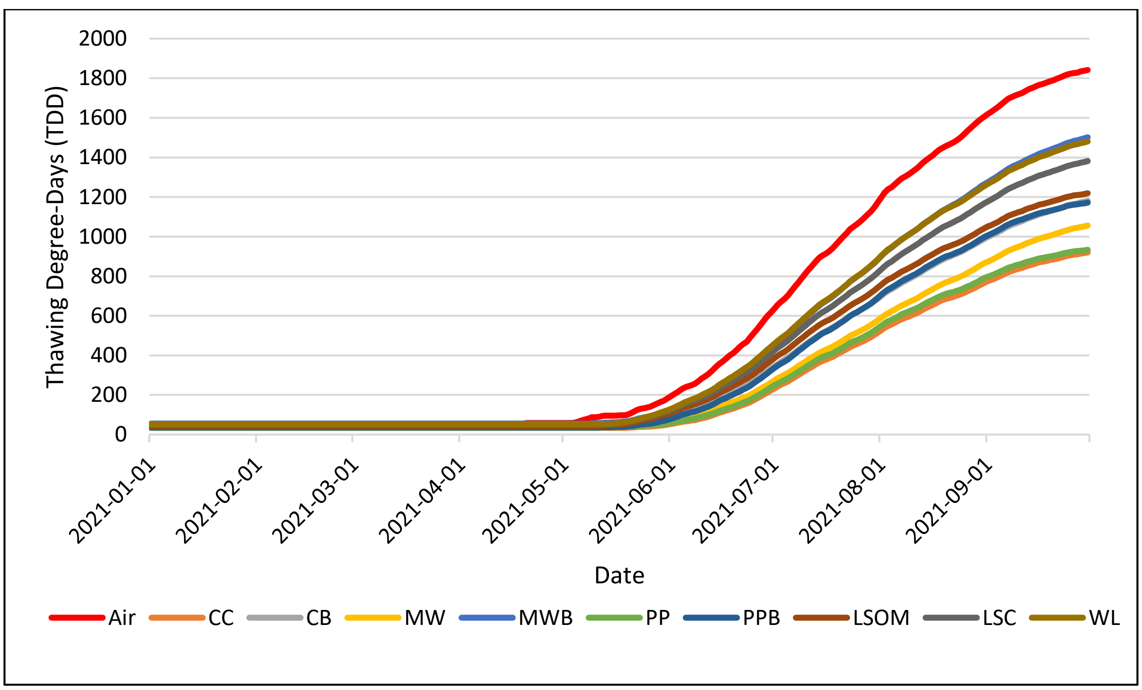

Figure 10. Measured cumulative Thawing degree-days (TDD) for all vegetation classes and one air temperature station WWS3 (red) from January 1st, 2021, to September 30th 2021.

3.5.3 Model outputs

3.5.3.1 MAAT

Modelled MAAT from October 2020 to October 2021 values ranged from -5 °C to -6 °C (Figure 11a). The root mean squared error (RMSE) value for MAAT was 0.0002 °C. Seasonally RMSE was highest in the winter at 0.007 °C and lowest in the summer at 0.0001 °C. The Environment and Climate Change weather station in Whatì was included in this model.

3.5.3.2 MAGST

Modelled MAGST from October 2020 to October 2021 values ranged from -1 °C to 3.5 °C (Figure 11b). The average RMSE value for MAGST was 0.77 °C. Seasonally RMSE was highest in the spring and summer at 1.56 °C and lowest in the fall (0.57 °C). Winter was similar to spring and summer at 1.54 °C. These higher RMSE's are due to the ground surface temperature models having difficulties taking the effects of soil moisture into account. Each vegetation class had similar temperature ranges, with the lowest temperatures found in mix-wooded forests and mix-wooded forest burnt (-0.98 °C) and the highest in mix-wooded forest burnt and low-shrub organic mat. (3.58 °C) (Figure 13). Average temperatures ranged from 1.38 °C in mix-wooded forest to 1.92 °C in coniferous forest and low-shrub clearing (Figure 3b).

3.5.3.3 n_t and n_f

Modelled n_f values ranged from 0.05 to 0.383 with an average value of 0.17 (Figure 11c). Vegetation classes with higher organic material such as peat plateau, peat plateau burnt, and low-shrub organic matter had lower average n_f values (0.16). While classes with less organic matter such as mix-wooded forests and mix-wooded forests burnt had higher average n_f values of 0.19 and 0.21. Modelled n_t values range from 0.4 to 0.84 with an average value of 0.7 (Figure 11d). This is a much higher value than n_f. Again, vegetation regions with higher organic matter have lower thermal connectivity (Obu et al., 2019; Smith & Riseborough, 2002). Coniferous forest, peat plateau burnt, and peat plateau have the lowest n_t values (0.55, 0.58 and 0.61). The rest of the vegetation classes were all around 0.7.

3.5.3.4 TTOP Model

Modelled TTOP from October 2020 to October 2021 ranged from -3.2 °C to 2.7 °C across the study area (Figure 10). TTOP had an average temperature of 0.32 °C with 31 % of the surface being classified as permafrost (having a temperature < 0 °C) and 69 % as non-permafrost (> 0 °C). Peat plateaus, coniferous forests, and low-shrub organic matter had the highest percentage of the ground being underlain by permafrost (99.7 %, 96 % and 71.6 %). Coniferous forest burnt and low-shrub clearing had the lowest percentage of permafrost (3.8 % and 4.4 %). TTOP temperatures decrease with increasing elevation. Areas with an elevation below 246.8 m a.s.l have an average temperature of 0.68 °C, whereas areas between 261.9 m and 282.7 m a.s.l have an average temperature of -0.29 °C. A similar trend is observed in the relationship with TPI as <-0.8 had an average temperature of 0.69 °C and 1.1 - 8.9 had an average -0.87 °C. Results show that low TTOP correlates with low MAGST and high n_f (Figure 11 and 12). This is similar to the results found in (Garibaldi et al., 2021).

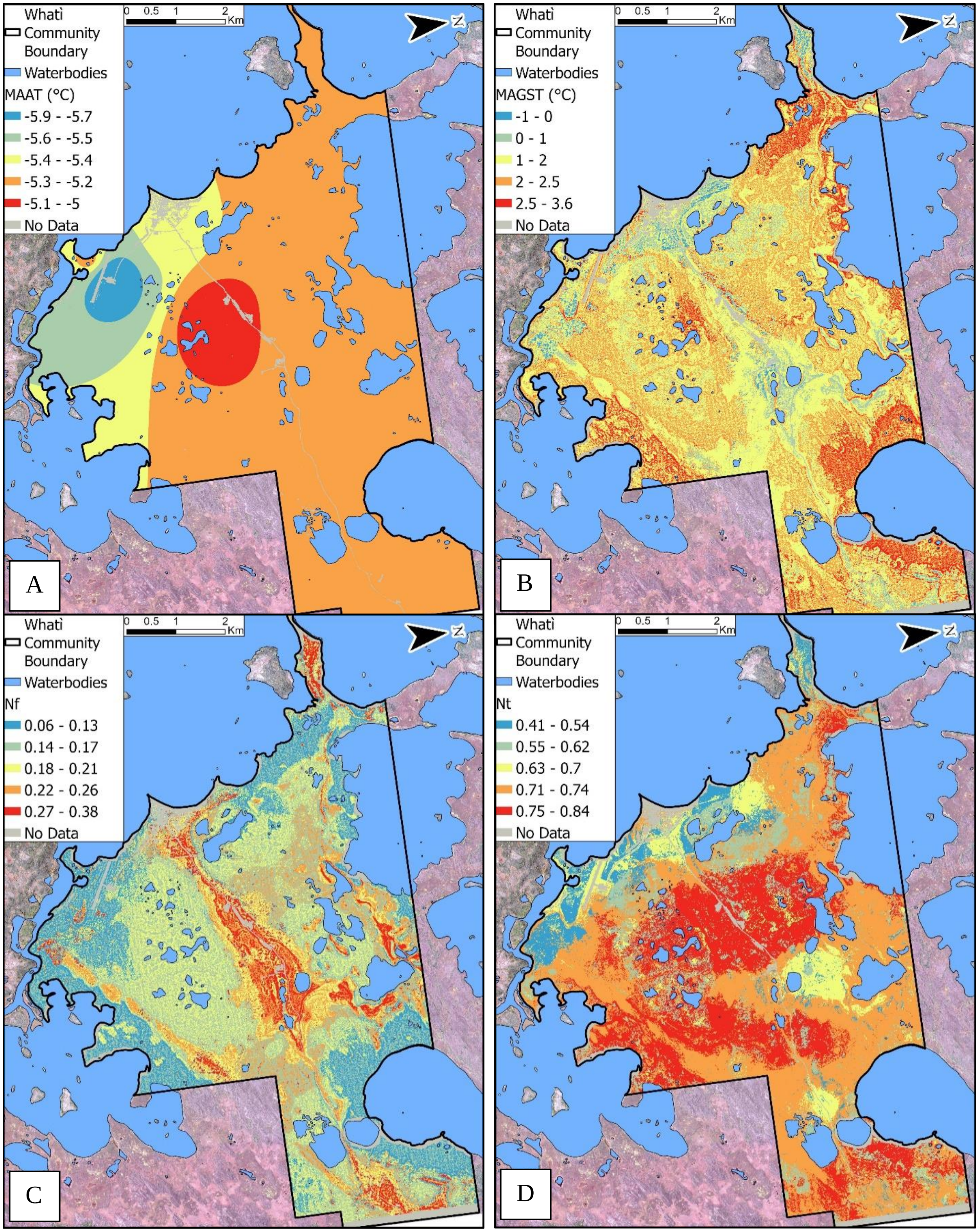

Figure 11. (A) Modeled MAAT over the study area for 2020/2021. (B) Modeled MAGST temperature ranges over the study area for 2020/2021. (C) Modeled n_f values over the study area for 2020/2021. (D) Modeled n_t values over the study area for 2020/2021.

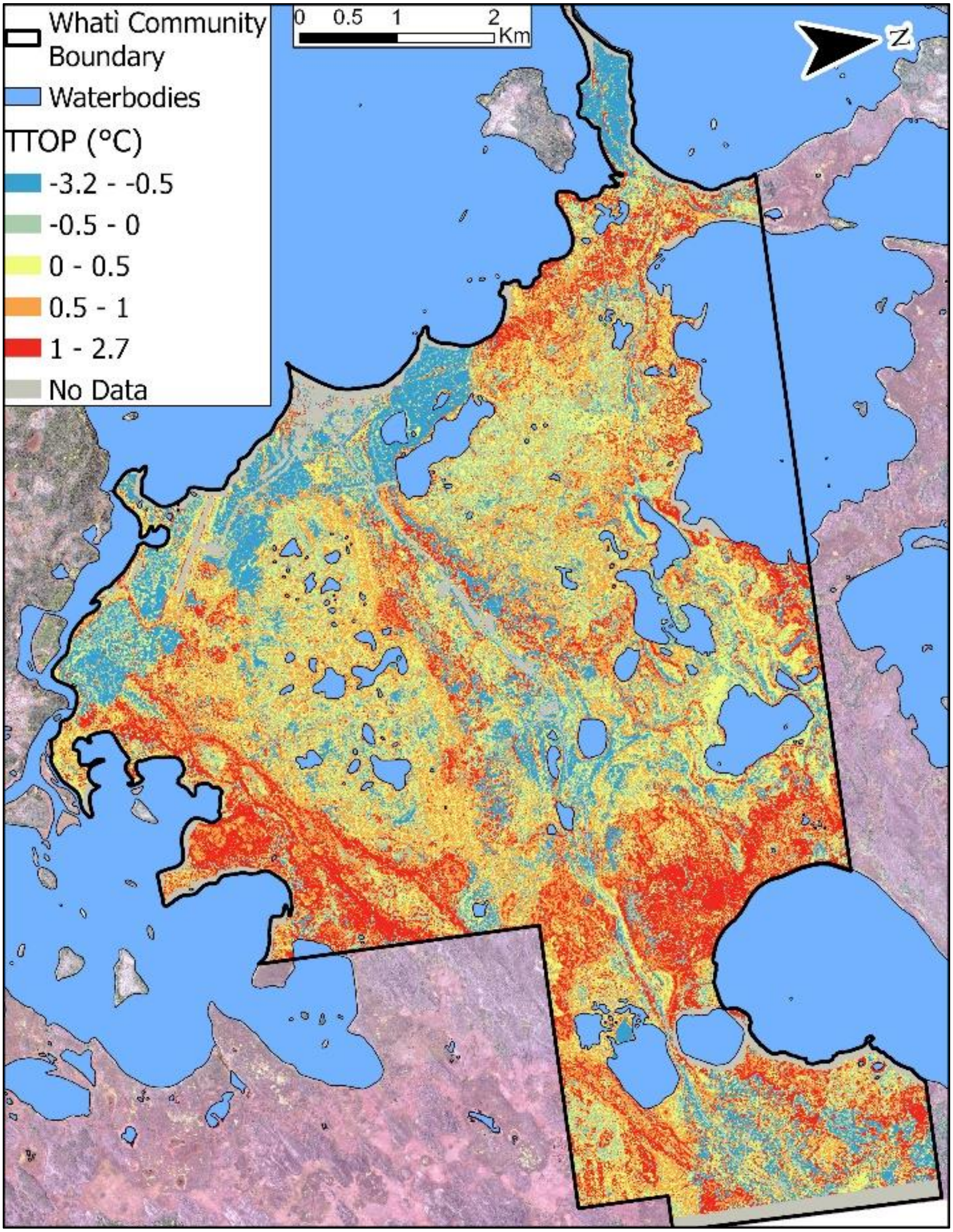

Figure 12. Modeled TTOP temperatures (°C) for the study area in 2020/2021.

3.5.4 TTOP and MAGST Comparison

Breaking down TTOP and MAGST, vegetation classes with high organic matter had the highest difference in average temperature between the TTOP and MAGST surfaces. This included peat plateau (2.52 °C), low-shrub organic matter (2.23) and coniferous forest (1.99 °C). Whereas disturbed areas and areas with low organic matter had the lowest differences between average temperature, burnt coniferous forest, burnt mix-wooded forest, low-shrub clearing and mixed-wooded forest (0.81 °C, 0.83 °C, 0.83 °C, 0.9 °C). Temperature ranges for vegetation classes in MAGST are consistent with average temperatures only ranging from 0.97 °C (coniferous forest) to 2 °C (wetland). Maximum temperatures range from 3.37 °C (peat plateau) to 3.58 °C (mix-wooded forest burnt and wetland). Minimum temperatures also stay consistent with variable vegetation ranging from -0.98 (coniferous forest, mixed-wooded forests and mixed-wooded forests burnt) to -0.5 °C (low-shrub clearing). Variations by vegetation class are greater in the TTOP surface. Average temperatures range from 0.24 °C (peat plateau) to 2.66 °C (mix-wooded forest burnt). Maximum temperatures range from -1.04 (peat plateau) to 1.12 °C (low-shrub clearing). Minimum temperatures have a similar result ranging from -3.16 (peat plateau) to -1.14 °C (low-shrub clearing) (Figure 13). Elevation shows a general trend of decreasing temperature with an increase in elevation. TPI shows a trend of warmer temperatures in hollows (-0.8) and cooler temperatures on peaks and ridges (8.9). This is observed in both the TTOP surface and the MAGST surface (Figures 14 and 15).

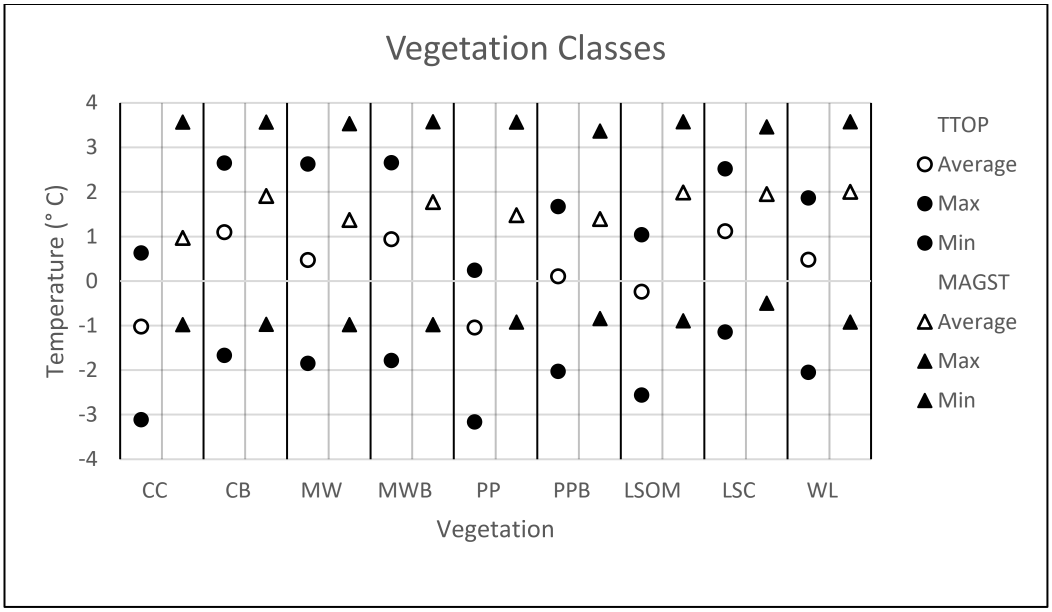

Figure 13. shows the average temperature and temperature ranges for the TTOP and MAGST surfaces for different vegetation classes.

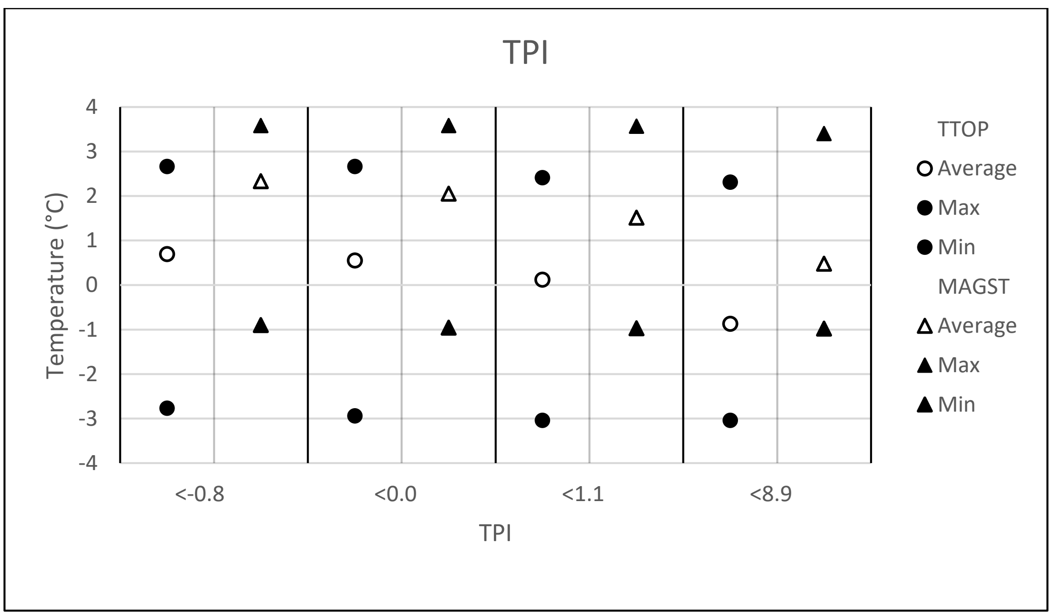

Figure 14. shows the average temperature and temperature ranges for the TTOP and MAGST surfaces for different TPI classes.

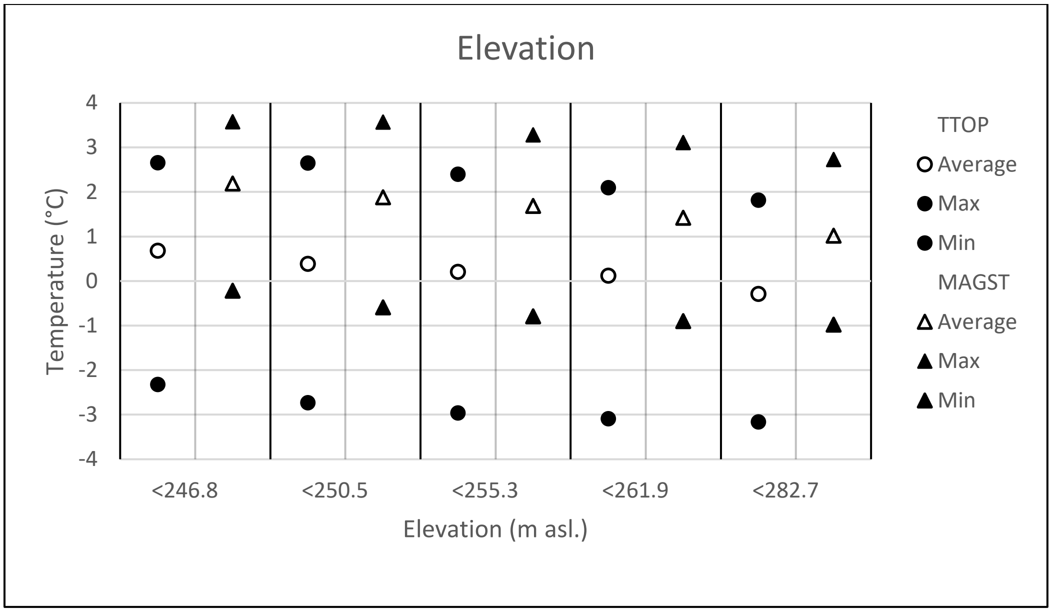

Figure 15. shows the average temperature and temperature ranges for the TTOP and MAGST surfaces for different elevation classes.

3.5.5 TTOP Accuracy Assessment

To assess the accuracy of the TTOP surface model output was compared to cryotic assessment sites (CAS) from Daly et. al (2022; Table 2). Of these 139 sites, 136 fell within the modelled study area. The TTOP model agreed with 85 out of 136 of the CAS or 62.5 %, meaning that 51 (37.5 %) did not agree. Ecosystem classifications that agreed the most with the CAS classifications were peat plateau, coniferous forest and mix-wooded forest burnt (16/16[100 %], 16/19[84 %] and 10/12[83 %]). Ecosystem classifications that agreed the least were low-shrub organic mat. and low-shrub clearing (2/9[22 %] and 4/10[40 %]) (Figure 16 and 17). Nineteen out of 136[14 %] of CAS were deemed false positive, meaning that the TTOP model indicated permafrost when it was not present. This primarily occurred in wetlands, mixed-wooded forests, and low-shrub clearings (38 %, 29 %, 50 %). 32 out of 136(23.5 %) were deemed false negative, meaning that the TTOP model indicated no permafrost when permafrost was present. This primarily occurred in peat plateau burnt, low-shrub organic matter and coniferous forest burnt (58 %, 56 %, 36 %).

Table 2. Cryotic assessment sites (CAS) from Daly et. al (2022) including vegetation class, description (Daly et al., 2022), number of sites (n), number of sites containing permafrost, and percentage of sites containing permafrost.

Variable	Class	Description	n	Permafrost	Permafrost (%)
Vegetation Classification	Coniferous Forest (CC)	Black spruce and tamarack tree stands w/, organic mat. layer including moss, lichen, Labrador tea, cinquefoil.	19	19	100
	Coniferous Forest Burnt (CB)	Same as Coniferous Forest with grass of Parnassus, sedges, and horsetails. Visible evidence of recent burn (2014).	14	6	42.9
	Mixed-wooded Forest (MW)	Aspen, birch, willow, spruce, alder w/ thin organic mat. layer. Rose, buffalo berry, bear berry, occasional thin layer of moss and lichen.	17	4	23.5
	Mixed-wooded Burnt (MWB)	Same as Mixed-Wood Forest w/ fireweed. Visible evidence of recent burn (2014).	12	2	16.7
	Peat Plateau (PP)	Visible plateau or hummocky terrain. Cloudberry, bog rosemary, white lichen, moss, Labrador tea, spruce tree stands.	16	16	100
	Peat Plateau Burnt (PPB)	Same as Peat Plateau with visible evidence of burn (2014).	26	26	100
	Wetland (WL)	Wet moss layer, grass, bog birch, fireweed, sundew, wax mertle, willow, cinquefoil, bog rosemary. High water table. Minimal resistance to soil probe.	13	1	7.7
	Low-shrub Organic, Matter (LSOM)	Coniferous Forest adjacent, similar organic mat., low-density to no tree cover. Juniper, willow, spruce, Labrador tea, moss, lichen, cinquefoil.	9	7	77.8
	Low-shrub Clearing (LSC)	Low-density paper birch, willow. Rose, horsetail, fireweed, and grass	10	2	20
Elevation	1	<246 m asl.	13	11	84.6
	2	246 - 250 m asl.	52	29	55.8
	3	250 - 255 m asl.	51	36	70.6
	4	255 - 261 m asl.	20	7	35
	5	261 - 282 m asl.	0	0	n/a
Topographic Positioning Index (TPI)	1	<-0.8	11	5	45.5
	2	-0.8 - 0.0	75	39	52
	3	0.0 - 1.1	47	37	78.7
	4	1.1 - 8.9	3	2	66.7

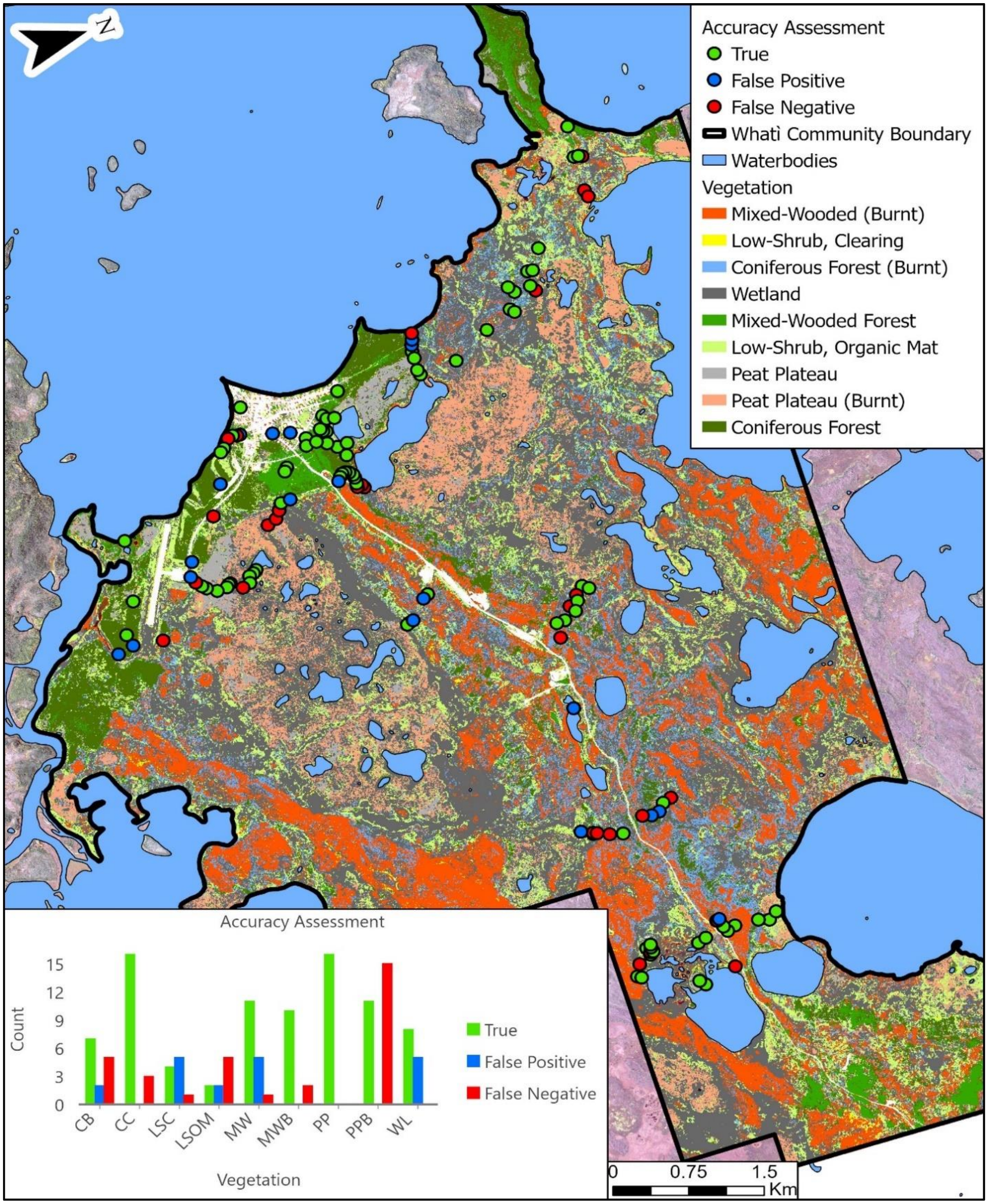

Figure 16. Accuracy assessment output comparing the TTOP model with cryotic assessment sites (CAS) (Daly et. al 2022). Overlaying vegetation surface. Accuracy Assessment: graph showing the amount of true, false positive and false negative sites for each vegetation class.

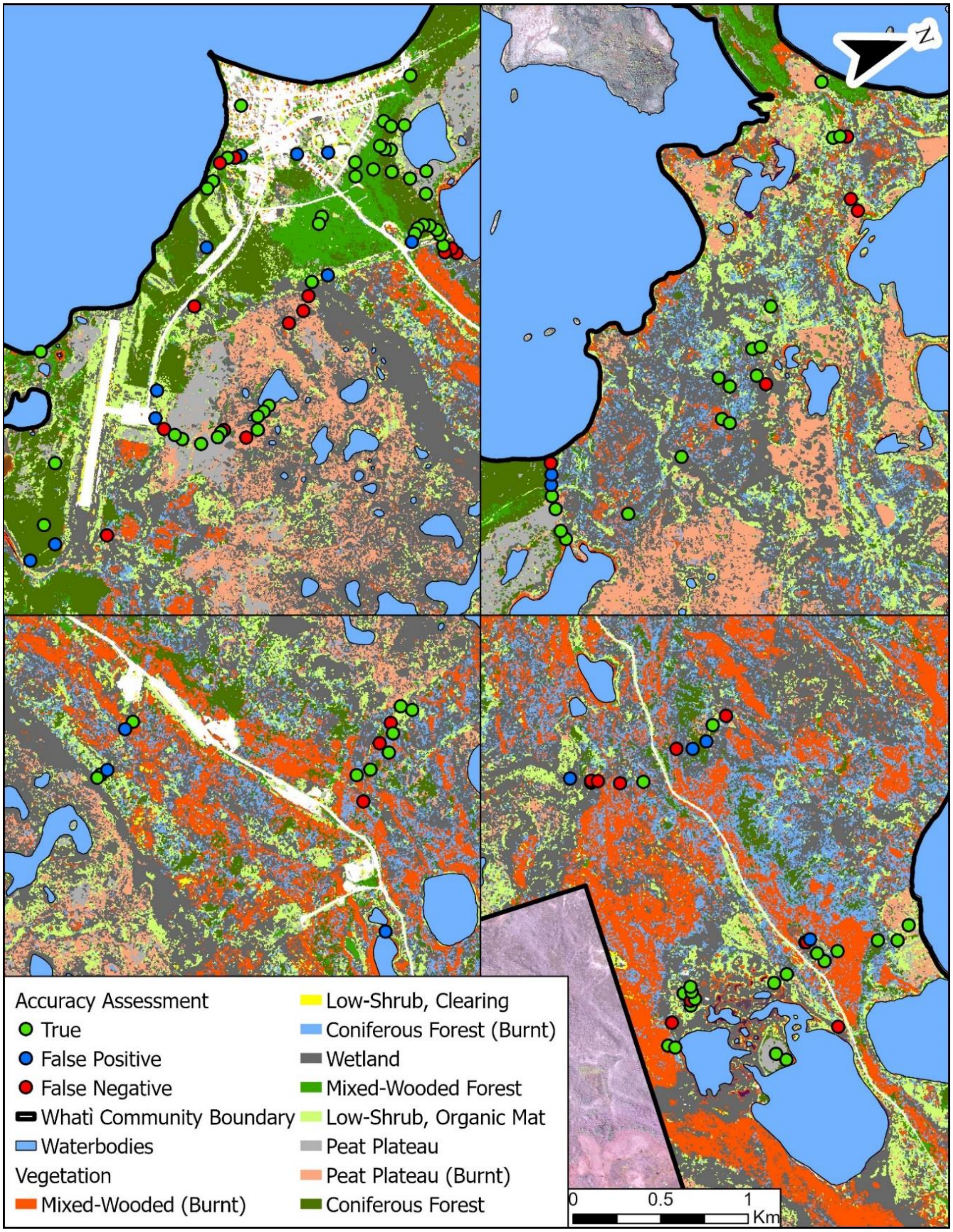

Figure 17. Study area sections to better show accuracy assessment outcomes. True (Green), False Positive (Blue), False Negative (Red).

3.5.6 Seasonal Frost and Permafrost Model

Running the seasonal frost model yielded a range of values between -0.6 °C to 3.9 °C, with an average temperature of 2.4 °C (Figure 18). The TTOP model was divided into cells with a temperature greater than 0 °C and cells with a temperature below 0 °C. The seasonal frost model was then run-on cells above 0 °C and merged with the TTOP cells below 0 °C. This generated a surface with a temperature range of -3.2 °C to 3.9 °C, with an average temperature of 0.55 °C, which is 0.23 °C higher than the TTOP model (Figure 18). In the region 29 % was underlain with permafrost. This is 2 % less than the TTOP surface. The accuracy assessment ran on the TTOP surface was also run on this surface yielding identical results. Running the seasonal frost model on the same cells produced a range of 0.42 °C to 3.9 °C with an average of 2.3 °C.

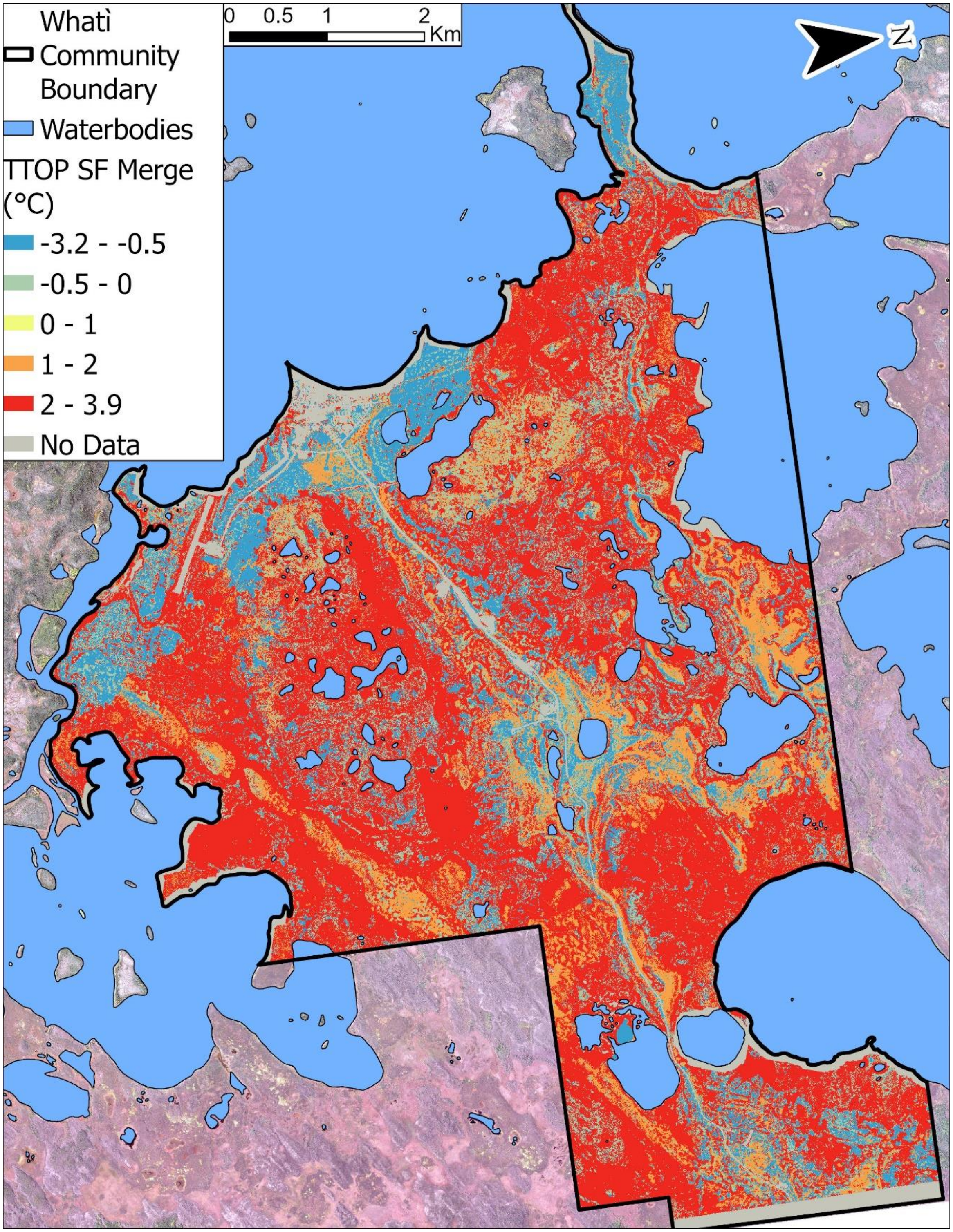

Figure 18. A merged surface of the TTOP model and the Seasonal Frost model, where the seasonal frost model was run on TTOP grid cells that were greater than 0 °C.

3.6 Discussion

3.6.1 Temperature Typicality

The TTOP model is an equilibrium model and therefore should be applied when the thermal conditions of the air and ground are stable and at equilibrium (Garibaldi et al., 2021; Riseborough, 2007; Wright et al., 2003). However, this concept is ideal and may not hold true under current conditions as much of the planet, especially in permafrost regions, is rapidly warming (Osterkamp & Romanovsky, 1999; Stuenzi et al., 2021; Vitt et al., 2000). As a result, it is difficult to apply the TTOP model in remote areas where long-term temperature data do not exist. In instances where limited data are available due to remoteness, temperature typicality has been used to show that conditions in the data collection period are representative of longer-term averages (e.g., Garibaldi et al., 2021). The TTOP surface in this study was collected during a period of air temperature within the standard deviation of a 50-year average (1970 – 2019). However, the data collection period was colder than the 10-year (2011-2021) average. This shows strong evidence of recent warming trends with the data collected during a relatively cold year compared to the recent average. Thus, a longer study over the last 5-years not including the data collection year (2020-21) may place the surface out of equilibrium with historical climate data. Although more data over a longer time is always preferred, this study utilized a method (GTN network) of capturing heterogeneity in a way that has only been used to model TTOP recently (Bonnaventure et al., 2017; Garibaldi et al., 2021). Due to the conditions in the year of data collection, we do not feel additional data would have drastically changed the outcome of the results or the conclusions on the usability of TTOP in boreal wetland environments. It must be stated, however, that caution must be used in relying strictly on the TTOP model for short datasets and that temperature analysis and typicality must be conducted. If the study had been conducted in a year that was deemed untypical (warmer or colder) the GTN network should still be able to capture the heterogeneity of the surface temperature. This is based on the idea that typically portions of the landscape which are prone to being warmer or colder or accumulating high or low levels of snow cover remain consistent from year to year even in atypically cold or warm years ((Garibaldi et al., 2021; Young et al., 1997). If this study had taken place in a non-typical year the spatial heterogeneity would still have been captured however the value of the results are likely to have been shifted towards the warmer or colder end of the spectrum.

3.6.2 TTOP and Binary Logistic Regression Model Comparison

Daly et. al (2022) ran a binary logistic regression (BLR) model for Whatì, that utilized 139 CAS recorded in August of 2019, as well as digital surface models to understand the distribution of near surface permafrost. The BLR model is a probability-based model and defines the overall permafrost amount according to the average of the surface itself (Lewkowicz and Ednie, 2004; Bonnaventure et al., 2012). The BLR model predicted 50 % or 30 km^2 of the study area had a 50 % or greater probability of being underlain by near-surface permafrost. This modelling technique was unable to account for permafrost which is a relic with the presence of a talik that has formed recently (Daly et al., 2022). The 50 % - 90 % value is consistent with the TTOP results (Obu et al., 2019) in that it is classified within the extensive discontinuous permafrost zone, although generally lower probability but more variability at higher resolution. Daly et al. (2022) modeled that 36 % of the study area had a probability of 99 % or greater. Although this value is different than the 50 % value assigned as the amount of permafrost in the Daly et al. (2022) model, a probability of >99 % is where the model has extremely high confidence in permafrost being present.

The TTOP model is a temperature-based model and defines permafrost as having a temperature below 0 °C (Obu et al., 2019; Zhang et al., 2000). In this study, the TTOP model predicted 31 % or 18.6 km^2 of the study area being underlain with permafrost (TTOP < 0 °C), showing a 19 % or 12.4 km^2 difference with the 50 % probability and 7 % difference with a 99 % probability. This variation between the two models can be a product of differences with respect to output or the way permafrost is defined. Utilizing the TTOP approach there is a firm cut off (0 °C) and thus the two are not as directly comparable as it might first seem. As an example, if a more liberal definition of TTOP is given (e.g. TTOP < 0.5 °C) when examining the overall permafrost amount, the percent underlain by permafrost increases drastically to 57 %. This shows that these models could be more comparable than first anticipated and that the spatial distribution as well as the overall amount of permafrost must be examined before direct comparison.

Vegetation classes where the two models had similar permafrost percentages included peat plateau, coniferous forest, and low-shrub organic mat. (Table 3). Vegetation classes that differed the most between the models were peat plateau burnt, low-shrub clearing, mixed-wooded forest burnt, coniferous burnt, and wetland. The other class mixed-wooded forest was in the middle. Based on this it can be understood that the two models had high agreements in areas with high permafrost percentages and vegetation classes with high amounts of organic matter, and as permafrost decreased so did the agreement of the two models. The TTOP model was much lower in permafrost occurrence in both burnt areas and areas with less amounts of organic matter.

Table 3. Compares the percentage of each vegetation class that is underlain by permafrost for both the TTOP model and the BLR model. As well as the percent of landcover that study area takes place.

Vegetation Class	TTOP (%)	BLR (%)	Study area (%)
Coniferous Forest (CC)	96	100	8.3
Coniferous Forest Burnt (CB)	3.8	34	9.2
Mixed-wooded Forest (MW)	2.9	17	4
Mixed-wooded Burnt (MWB)	7	26.1	18
Peat Plateau (PP)	99.7	99	3.2
Peat Plateau Burnt (PPB)	38.3	99.9	8.7
Wetland (WL)	12.7	32.9	36.6
Low-shrub Organic, Matter (LSOM)	71.6	71	12.7
Low-shrub Clearing (LSC)	4.4	3.9	0.5

As expected, both the TTOP and BLR models show a decrease of permafrost in burnt ecosystem classes compared to the unburnt counterpart (Burn, 1998; Holloway et al., 2020; Yoshikawa et al., 2002). Large discrepancies between the TTOP and BLR model in burnt ecosystems can be attributed to ground surface temperatures warming post-fire while the organic matter present in the ecosystem pre-fire continues to insulate the permafrost beneath it (Holloway et al., 2020; Shur & Jorgenson, 2007). Warmer ground surface temperatures are observed in the summer at the GTNs for each of the burnt sites as opposed to their unburnt counterparts. Permafrost in areas with high organic matter tends to be more resilient to forest fire due to higher soil moisture and low drainage properties (Holloway & Lewkowicz, 2020; Holloway et al., 2020; Jafarov et al., 2013; Jiang et al., 2015). This can be seen as average summer temperatures increased by at least 2 °C for each of the burnt ecosystems when being compared to their unburnt counterpart. Furthermore, most of the areas with high organic matter contained some amount of *sphagnum* moss which assists with permafrost preservation post-fire as its thermal conductivity doesn't change post-burn (Holloway & Lewkowicz, 2020; Zhang et al., 2015). Results in Daly et al. (2022)

indicate an increase in active layer depth between peat plateau and peat plateau burnt. However, they also indicate a very small increase in permafrost probability between peat plateau and peat plateau burnt (99 % and 99.9 %). Historically, peat plateaus that have been affected by a forest fire lose permafrost based on burn severity (Alexander et al., 2018; Jafarov et al., 2013). Therefore, the amount of ecosystem peat plateau burnt underlain with permafrost is somewhere between the two models.

3.6.3 Accuracy assessment

The accuracy assessment shows that the TTOP model is more like the CAS ground truthing pits than it is to the BLR model when comparing the percent of CAS pits that detected permafrost to the percentage of permafrost coverage by the ecosystem. The average difference for each ecosystem type between the TTOP model and the CAS ground truthing pits is 16 %, while the average difference for the TTOP model and BLR model is 19.5 %. When burnt ecosystem classes are removed (coniferous burnt, peat plateau burnt and mixed-wooded forest burnt) those differences go down to 4.7 % and 10.7 %. These differences can be attributed to the increase in GTN temperatures for burnt ecosystems in both winter and summer.

When broken down by ecosystem, the accuracy assessment showed results like the BLR model comparison as areas with high amounts of organic matter like peat plateaus and coniferous forest had high accuracy rates (100 % and 84 %). 100 % of the CAS in these ecosystems had permafrost. Another ecosystem with a high accuracy was mixed-wooded forest burnt (83 %). Only 2/12 (16.7 %) of the CAS in this ecosystem had permafrost. This is only a 9 % difference from the TTOP estimation of 7 %. Most false negative occurrences were in peat plateau burnt ecosystems. This once again can be attributed to an increase in surface temperature post-fire while the thermal conductivity of the ecosystem remains similar to pre-fire conditions (Holloway et al., 2020). False positives were primarily found in wetlands, low-shrub clearings, and mixed-wooded forests. This can be due to higher amounts of soil moisture in these areas, not allowing the ground to warm enough in the summer or giving a temperature high enough for the model to be greater than 0 °C. Due to latent heat, these wetter areas are able to dissipate more energy than drier areas (Riseborough, 1990). Poorly drained soils tend to have much higher thermal conductivities when frozen in winter than when unfrozen in summer (Romanovsky & Osterkamp, 1995). This can cause rapid heat loss in the winter and slower warming in the summer leading to a greater thermal gradient between the ground surface and TTOP (Daly et al., 2022; Jorgenson et al., 2010; Romanovsky & Osterkamp, 1995).

As the TTOP model is widely used in regional and continental scale models across Canada and all over the world (Bonnaventure et al., 2017; Garibaldi et al., 2021; Kukkonen et al., 2020; Smith & Riseborough, 2002; Way & Lewkowicz, 2016) it was the primary model used in this study. An alternative model the seasonal frost model was also explored for areas the TTOP model identified as being greater than 0 °C. Due to frozen ground having a higher thermal conductivity than thawed ground this model better takes into account the thermal conductivity of the ground under seasonal frost conditions (Romanovsky & Osterkamp, 1995; Smith & Riseborough, 1996). When using this model in conjunction with the TTOP model the average temperature increases to 0.5 °C, 0.2 °C higher than the TTOP model. However, for areas above 0 °C, when subtracting the seasonal frost model from the TTOP model, the average difference is 1 °C, showing that the majority of TTOP temperatures are greater than seasonal frost temperatures and that the TTOP model is sufficient for this study area.

3.6.4 Comparison to other TTOP Models

Due to the simplicity and low input requirements of the TTOP model it has been utilized to generate high-resolution maps (< 1 km) of specific regions as well as the entire country in Canada and other parts of the world (Bonnaventure et al., 2017; Garibaldi et al., 2021; Juliussen & Humlum, 2007; Obu et al., 2019; Smith & Riseborough, 2002; Way & Lewkowicz, 2016). Larger scale models can produce inaccuracies as local variations in vegetation, topography, snow cover and soil can produce temperature variations of several degrees in MAGT over a small area (Judge, 1973; Smith & Riseborough, 2002). Obu et al. (2019) uses remotely sensed data as inputs to the TTOP model to generate a 1 x 1 km permafrost temperature and zonation map for the entire Northern hemisphere. In this model permafrost is defined as an area with a MAGT below 0 °C (Zhang, 2005). It modelled that the region surrounding Whatì has a MAGT of -2 °C to -1°C and falls into the discontinuous permafrost zone, being 50 - 90 % underlain by permafrost. Using a 1 km^2 resolution in this study area would break it up into 60 parts leading to a generalization of the model inputs it uses (land surface temperature, vegetation cover, wetness, precipitation). This study has shown that the vegetation and DEM variables in this model are so heterogeneous that 1 km^2 resolution is not high enough for an accurate study of permafrost presence.

The map produced by Heginbottom et. al., (1995) shows the distribution and boundaries of permafrost and ground ice in Canada. The map is produced on a national scale (1:7 500 000) and depicts similar results to the Obu et al., (2019) product. It indicates that Whatì falls into the discontinuous permafrost zone (50 % - 90 % permafrost coverage) and has a MAGT of 0 °C to -2 °C with low ground ice. Similarly, Henry and Smith (2000) produced a ground temperature map of Canada with a resolution of 10 x 10 km and found that the region of Whatì had a MAGT of 0 °C to -2°C. Smith and Riseborough (2002) ran the TTOP model on a national scale to map limiting conditions on permafrost zones in Canada. Also placing TTOP in Whatì in the discontinuous permafrost zone (50 - 90 % permafrost coverage). Like Obu et al., (2019) the maps produced by Heginbottom et. al., (1995), Henry and Smith (2000), and Smith and Riseborough (2002) are produced on a national scale and able to map out the general trends of MAGT and permafrost distribution in Canada but are not able to account for the heterogeneity of boreal landscapes.

High-resolution TTOP models have been shown to have similar errors in a study conducted by Way and Lewkowicz (2016). Their model failed to predict permafrost where it was known to occur in palsa fields. The study claims that one of the reasons this occurs may be due to the fact that the palsas are out of thermal equilibrium with the recent climate (Riseborough, 2007), much like the permafrost in boreal peat plateaus. The permafrost in these palsas could be considered climate-driven ecosystem-modified or ecosystem-protected (Shur & Jorgenson, 2007). As the TTOP model is climate-based, high-resolution studies may be better suited to model MAGT for permafrost that is climate-driven. This primarily occurs in the High Arctic. It has shown that it can accurately model ground temperature variability in the High Arctic (Bonnaventure et al., 2017; Garibaldi et al., 2021) and it consequently assist with explaining ground temperature drivers. This study has found that permafrost in Whatì is climate-driven ecosystem-modified affecting the usefulness of the TTOP model here.

3.6.5 Disturbed vs. Undisturbed Regions

Forest fire frequency and severity has and is expected to increase with climate change in boreal forest regions (Kasischke & Turetsky, 2006; Wang et al., 2015; Wotton et al., 2010). Forest fires affects the energy balance and thermal conductivity of the ground by altering or decreasing the thickness of the organic layer, changing the albedo and the total solar radiation reaching the surface as well as snow cover (Holloway et al., 2020; Jorgenson et al., 2010; Yoshikawa et al.,

2002) Therefore, it is important to understand its implications on permafrost presence and degradation. Fire can increase surface and soil temperatures for boreal forests immediately following the fire and lasting decades later (Gibson et al., 2018; Li et al., 2021; Nossov et al., 2013; O'Donnell et al., 2011; Yoshikawa et al., 2002; Zhang et al., 2015). The community of Whatì was impacted by a fire in 2014, burning roughly 84 % of the study area (Daly et al., 2022). This study was conducted during the period of maximum active layer thickness which generally occurs 5 to 10 years post-fire (Yoshikawa et al., 2002). The temperature increase is observed in the TTOP model between the three ecosystems where both burnt and unburnt regions can be directly compared. In coniferous forests there is an average MAGT increase of 2.1 °C, in peat plateau, there is an increase of 1.1 °C, and in mix-wooded forests there is an increase of 0.46 °C. The increase in temperatures can be part of the reason why results in the TTOP model showed a decreasing presence of permafrost for burnt areas in comparison to the BLR model and CAS sites. However, these surface temperature increases seem to have had minimal effects on the permafrost presence of the peat plateau burnt CAS sites. This is due to peatlands being more resistant to burn because of their high moisture and latent heat contents (Daly et al., 2022; Jafarov et al., 2013). The coniferous forest, however, had a large difference between burnt and unburnt sites for both the TTOP model and CAS sites. A burnt forest loses its tree canopy and thus its ability to intercept snow (Holloway et al., 2020), leading to a deeper snowpack, greater insolation and a lower n_f. This combined with a decreased organic layer and albedo can cause permafrost loss (Holloway et al., 2020; Jafarov et al., 2013; Smith et al., 2015). The study illustrated that the greater amount of disturbance the more difficult it is for an area to be modelled by TTOP. This idea is shown in the number of false negatives that occurred in disturbed areas regardless of original vegetation type.

3.6.6 Practicality and Perturbment for Climate Change

As areas of high latitude are currently experiencing rapid temperature warming, permafrost thaw in arctic and boreal regions is expected to increase (Garibaldi et al., 2021; Jorgenson et al., 2001; Serreze & Barry, 2011; Swanson et al., 2021). An advantage to the TTOP model over the BLR model and why this study was conducted is its ability to be modified to model the change in permafrost distribution with climate change. Annual data from ClimateNa (AdaptWest, 2015; Wang et al., 2016) use climate change scenarios projecting MAATs for various climate change scenarios for future years (Wang et al., 2016). These scenarios will alter the TDD and FDD of the ground surface within the study area and inputting that into the TTOP model can give modeled insight into future ground temperatures. The will allow the study to understand how permafrost under different ecosystems will respond to warming ground temperatures under equilibrium conditions.

The effect climate has on permafrost will vary depending on a region's topography, soil type, moisture, vegetation and snow (Jorgenson et al., 2010). Combining the results of this study with the CAS from Daly et. al, (2022) has shown that organic matter and soil moisture in these boreal regions develop MAGT that are cooler than MAGST consistent with what was found in Jorgensen et. al (2010). In this study, they indicate that the thickness of organic matter and moisture have a major effect on MAGT. Allowing permafrost in ecosystems with these characteristics to be more resilient to climate change.

3.5.6 Uncertainty, improvements, and future work

The limitations and uncertainty in this study result in the TTOP model being an equilibrium model. Even though it has proved to be successful in other regions and on other scales (Bonnaventure & Lewkowicz, 2008; Garibaldi et al., 2021; Obu et al., 2019; Way & Lewkowicz, 2016), inaccuracies can be attributed to permafrost in peat-rich areas being out of equilibrium with the current climate and temperature. In some instances, the 2 m x 2 m vegetation classification did not match the ecosystem noted in the field. In cases where field stations and GTNs were placed, the vegetation classification was edited but it still may contain inaccuracies. The model also omits certain metrics that may assist a more accurate output, adding surficial data or other adding additional metrics and sensors that collect data on soil moisture, organic layer thickness and snow depth could play a larger role in improving the accuracy of the model rather than increasing the length of time of the study.

Future work on this study could involve implementing these metrics into the model to see if they affect MAGT and permafrost distribution. This study could also be combined to with the research conducted in Daly et. al, (2022) in northern communities in different regions such as Fort McPherson or Inuvik.

3.7 Conclusion

This study demonstrates that a climatically driven TTOP is a poor predictor of near-surface permafrost in a boreal forest environment and should be verified or tested using ground truthing techniques. The model can be used to illustrate the heterogeneity of ground temperature in this environment. It shows that permafrost presence in a boreal wetland ecosystem is not solely climate dependent, with distribution relying heavily on the heterogenous nature of the ecosystem. The TTOP model was found to have a 62.5 % accuracy rate with most inaccuracies found in burnt regions where permafrost was present but out of equilibrium with the current ground temperatures. The heterogeneity of the vegetation, TPI and elevation allow for considerable variation in the ground surface and TTOP temperatures throughout the study area ranging from -1 °C to 2.6 °C and -3.2 °C to 2.7 °C. Areas with thick amounts of organic matter are found to have lowest TTOP, while areas that underwent natural or artificial disturbance have higher TTOP. The following conclusions can be drawn from this study:

- The assessment of temperature typicality is essential for a TTOP model driven by short-term climate data. As most permafrost landscapes are not in climatological equilibrium unseasonably warm or cold years can skew the model results. Establishing typicality allows for spatial heterogeneity to be examined even with a temporally short dataset.
- The high-resolution TTOP model in this study was applied to estimate the amount of permafrost in this region (<0 °C) to be 30 %. This is a lower estimation compared to coarser resolution TTOP models that cover a larger region which estimates 50 - 90 % permafrost coverage utilizing the same permafrost classification method. When compared to the Whatì BLR model that utilized Cryotic Assessment Sites (CAS), 50 % permafrost cover was

estimated with 36 % of the area having > 99 % probability of permafrost. Although these models are not directly comparable, this highlights the potential drawbacks of utilizing a climatically driven model to map near-surface permafrost in a time of climate warming. It is thus likely that more permafrost is present around Whatì which the TTOP approach is not sensitive enough to detect it without calibration by ground truthing using CAS.

- Discrepancies and inaccuracies from the TTOP model can be attributed to ground temperatures being out of equilibrium with the current air temperatures. This is most evident in burnt ecosystems where the ground temperatures are out of equilibrium with the ground surface and air temperatures causing false negatives to be recorded.
- This study utilized a combination of the TTOP model for permafrost environments and a seasonal frost model for seasonally frozen portions of the study area. The seasonal frost model, an idea that must be considered in warmer periglacial environments, did not yield enough change for it to be an effective tool in this study area.
- Although we feel the TTOP model may not generally be the best approach for modelling permafrost in this boreal wetland area one advantage is the ability to model permafrost for future climate scenarios. Giving an understanding of how permafrost in different ecosystems will react to warming temperatures under equilibrium scenarios.
- The use of a ground temperature node (GTN) network is essential for modelling using TTOP. The GTN network captures additional data across ecosystems that would otherwise not be seen showing the heterogenous nature of ground temperatures even in areas of mostly uniform air temperature.

Chapter 4: Conclusions

4.1 Chapter Outline

The objectives of this research are to examine the validity of a climatically driven permafrost model in a boreal wetland environment, as well as to better understand the heterogeneity of ground temperatures of the discontinuous permafrost zone around Whatì NT. To reach these objectives a network of weather stations and GTNs were deployed throughout the study area to record hourly temperature data for a full calendar year. Using this network, the thermal conductivities of the different ecosystems and topographies were modeled allowing a permafrost distribution map to be generated. This study examines the hypothesis that a TTOP approach using a GTN network can determine the spatial distribution of permafrost, while providing insight into permafrost thermal state that is equivalent in accuracy to models created using ground truthing techniques. Finally, this study researched the effects of ecosystem disturbance such as fire on the thermal conductivity of different boreal forest ecosystems. The purpose of this chapter is to summarise major findings and conclusions, discuss how these findings might relate to other studies and their significance, and make recommendations for future research related to this topic.

4.2 Thesis Objectives and Major Findings

A TTOP model was produced using the hourly temperature data collected from the GTN, MCS and WWS network as well as the study site local variables affecting MAGT (vegetation, elevation, TPI). The TTOP model produced a permafrost distribution map where 30 % of the ground was underlain with permafrost, with a 62.5 % accuracy based on CAS sites where ground truthing had occurred. Vegetation types with high amounts of organic matter and permafrost had higher accuracy rates than areas with less. The TTOP model estimated that 30 % of the ground was underlain by permafrost. When compared to other models this is an underestimation. The BLR model from Daly et al. (2022), a high-resolution ground truthing model in the same study site, estimated 50 % of the ground was underlain by permafrost. Lower resolution TTOP models like Obu et. al, (2019) and Smith & Riseborough also estimated that 50 - 90 % of the region was underlain by permafrost. The majority of these inaccuracies occurred in burnt peat plateaus where the MAGT was out of equilibrium with the MAGST. These burnt regions also lead to discrepancies between the TTOP model and the BLR model produced in the same area by Daly et al. (2022). These regions are at the greatest risk of permafrost thaw as they are already in out of equilibrium with the current ground surface temperatures. This was also seen in Way et al. (2016) where palsa bogs failed to predict permafrost where it was present.

Using the GTN and climate network, the TTOP model was able to compare the heterogeneity of MAGT of different ecosystems throughout the region. With the highest average temperatures occurring in low-shrub clearing and coniferous burnt (1.12 °C and 1.1 °C) and the lowest average temperatures occurring in peat plateau and coniferous forest (-1.04 and -1.02). These temperatures can also vary depending on the TPI and elevation the ecosystem is located in. Temperature ranges also vary based on ecosystem., TPI and elevation.

4.3 Significance of findings

The TTOP model is widely used based on its simple inputs and successful use on continental scales (Obu et al., 2019; Way & Lewkowicz, 2016). It uses the differing thermal conductivities of the study area to model ground temperature. When applied to high-resolution data in boreal forest environments, the study found that solely using a TTOP model may lead to underestimations in the amount of permafrost being modelled. Showing that even though the model is able to show heterogeneity in ground temperatures throughout the study area it is not the best suited model for capturing near surface permafrost. If used in these environments it should be in conjunction with ground-truthing data as the MAGT, for some ecosystems may be out of equilibrium. This study emphasizes the need for these models to be tested. This is shown in comparing regions where permafrost was present in the BLR and not modelled in the TTOP model. These ecosystems are at risk of thaw as they were detected to have permafrost at the CAS but are out of equilibrium with the current MAGST. Ecosystems with the lowest agreement and most at risk were found to be modified ecosystems either anthropogenically (clearing) or naturally (fire) as these are mixed-wooded forest burnt, low-shrub clearing and coniferous burnt.

4.4 Future Work

The findings of this research can also be used in conjunction with climate models SSP 126 2040 and 2070 from Wang et al. (2016) to understand what ecosystems are most at risk to climate change. If this study were to be redeployed in other communities in the region, such as Gamètì and Wekweètì, it should be done in conjunction with ground truthing techniques. This study could be more accurate in areas with greater n_f and n_t values in the higher arctic such as Fort Mcpherson or Fort Good Hope. The sensors used in this study were redeployed and it would be interesting to see how the TTOP model develops and changes after being conducted over a longer time span. The model also omits certain metrics that may assist a more accurate output. Therefore, adding surficial data or other metrics such as soil moisture or organic layer thickness could play a larger role in improving the accuracy of the model rather than increasing the length of time of the study. Future work on this study could involve implementing these metrics into the model to see if they affect MAGT and permafrost distribution.

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